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# Chemical Stimulation of Lightwood in Southern Pines

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Pesticides used improperly can be injurious to man, animals, and plants. Follow the directions and heed all precautions on the labels.

Store pesticides in original containers under lock and key-out of the reach of children and animals — and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides when there is danger of drift, when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment if specified on the container.

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Do not clean spray equipment or dump excess spray material near ponds, streams, or wells. Because it is difficult to remove all traces of herbicides from equipment, do not use the same equipment for insecticides or fungicides that you use for herbicides.

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Note: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the Federal Environmental Protection Agency, consult your county agricultural agent or State extension specialist to be sure the intended use is still registered.

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U.S. DEPARTMENT OF AGRICULTURE

# Chemical Stimulation of Lightwood in Southern Pines

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## ABSTRACT

When applied to bole zylem tissue, paraquat, a bipyridylium herbicide induces lightwood formation (resin soaking) within the trunk of living pines. All southern pines respond and there is reason to believe that all members of the genus *Pinus* will react similarly. Other coniferous genera, however, show little if any significant reaction to paraquat. The amount and rate of oleoresin enhancement are functions of pine species, wounding method and extent of wounding used in applying paraquat, paraquat cation concentration, and time duration following treatment. Resin-soaking is essentially a wound response much magnified by the paraquat action within the tree. Bark beetles are much more strongly attracted to paraquat-treated trees than to adjacent pines identically wounded but not given paraquat. Fear of creating a bark beetle epidemic has probably hindered widespread application of lightwood technology, but this fear is unfounded. There is no instance where heavily attacked, paraquat-treated stands caused further beetle infestation. Beetle attack varies by season of treatment and wounding method, and is positively correlated with severity of wounding and especially the paraquat cation concentration used. Increases in wounding severity, paraquat concentration, or both, also increase oleoresin yield, but in progressively declining amounts. Therefore, the moderate paraquat treatments that we recommend will produce oleoresin yields only 10 to 15 percent less than those of severe treatments, and incur acceptable, often negligible, losses from beetle attack. These treatments will enhance oleoresin content of the wood from 100 to 150 percent; an increase from about 88 lb/100 $ft^3$ to 190 lb or more for slash pine, and from about 64 lb/100 $ft^3$ to 125 lb or more for loblolly pine.

**Keywords:** *Pinus taeda, Pinus elliottii,* paraquat, herbicide, oleoresin, resin soaking.

## INTRODUCTION

The general purpose of the research summarized here was to find the means to furnish the economy with an additional supply of oleoresins, which are made up of unsaturated hydrocarbon compounds that are very useful as chemical feedstocks. Because the source is renewable, oleoresin can be produced in perpetuity and the technology has negligible environmental impact. If the treatments proved profitable, we hoped to get them into commercial use as rapidly and efficiently as possible.

The United States has an energy problem that makes new sources of petrochemical substitutes or supplements most welcome. Increased production of oleoresin in living pines could become such a source. Oleoresin is a generic term for those solutions of isoprenoid compounds produced by conifers and other plants, which individually are called resins. Although subject to some oxidation, oleoresins are basically hydrocarbons. Oleoresin is composed primarily of resin acids dissolved in terpenes, which when separated by distillation produce resin and turpentine, respectively. In southern pines, by far the most important source in this country, resin acids of mostly abietic and primaric types constitute the rosin, and the turpentine consists essentially of alpha and beta pinenes (Drew and others 1971; Mirov 1967). Because of their historic use for ship caulking, these commodities from oleoresin are termed "naval stores." The present supply is from three sources: **(1) Gum naval**

**stores.** Living pines are tapped and oleoresin collected, in this country, exclusively from two southern pines, longleaf (*Pinus palustris* Mill.) and slash (*P. elliottii* Engelm. var. *elliottii).* (2) **Wood naval stores.** Oleoresins are obtained by solvent extraction from the heartwood-rich remains of virgin southern pine stumps. This stump heartwood is resin-soaked and is commonly known as "lightwood" because of its traditional use as kindling in the South. Stumps from the much younger, second-growth timber are mostly sapwood and have little resin accumulation. (3) **Sulfate naval stores.** Oleoresins are obtained as byproducts from the kraft pulping process, which is the most common method for producing paper and cellulose products from southern pines. The gum, wood, and sulfate sources contribute 2, 25, and 73 percent, respectively, of the current United States oleoresin production, which is nearly 1 billion lb (Zinkel 1975b). The sulfate source is clearly the most important, and its production continues to increase while those of the other two decrease due to high labor costs (gum naval stores) and the dwindling supply of virgin pine stumps (wood naval stores). Production from kraft pulpmills is governed, in effect, by the byproduct recovery efficiency, the volume or quantity of pulpwood processed, and especially the oleoresin content of the pulpwood. Production from the wood naval stores industry could also rise if new supplies of wood with sufficiently high oleoresin content were available.

In 1973, our Forest Service naval stores researchers reported a discovery that promises to solve this impasse--a method that can dramatically increase the oleoresin content of young sapwood trees (Roberts 1973; Roberts and others 1973). Such trees account for the overwhelming bulk of our present southern pine timber crops and will become even more important in the future. The bipyridylium herbicides diquat or paraquat, particularly the latter, when applied to bole tissue will induce lightwood formation (resin-soaking) within the trunk of the living pine. All southern pines respond to paraquat by producing lightwood (Peters and Roberts 1976).

All pines of North America tested thus far produced resinosis after paraquat application (Conner and others 1977; Rowe and others 1976). There is reason to believe that all species of the genus *Pinus* will respond, but other coniferous genera such as *Thuja, Abies, Tsuga, Picea, Larix,* and *Pseudotsuga* do not show an economically significant reaction to paraquat (Kiatgrajai and others 1976a, 1976b; Sandberg and others 1977). The magnitude of response, in practical terms, is not known for northern and western pines. However, naval stores production in the United States is dominated by the South, where more than 90 percent of the oleoresin is produced. The reasons are both biological and technical; the major southern pines have a higher natural oleoresin content than northern and western species, and most southern pulpmills use the kraft process which allows byproduct recovery. Consequently, the opportunities for profitable lightwood reduction are in the South, and most of the pertaining research has been done there.

In July 1978, the EPA paraquat label was amended to allow paraquat to be used commercially for lightwood induction in all southern pines except sand pine (*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.).

### *Oleoresin Production Potential*

What is the magnitude of this potential silvachemicals source? Various paraquat treatments can at least double tree oleoresin content, producing about 80 lb of additional oleoresin in each cord of pulpwood (a cord contains about 80 $ft^3$ of solid wood). Within the 13 Southern States of USDA Forest Service Region 8, the southern pines, principally loblolly *(P. taeda* L.), slash, longleaf, and shortleaf (*P. echinata* Mill.) dominate on about 72.7 million of the 204.2 million acres of commercial forest land. On an additional 31.9 million acres, southern pines are present in admixture with hardwoods. These pines contain approximately 86.8 billion $ft^3$ of wood, about 1.085 billion cords, in growing stock 5 in. or larger in diameter (USDA Forest Service 1973, 1975a). Additional wood is accumulating at the rate of about 1.4 billion $ft^3$ annually. If all this merchantable growing stock were treated with paraquat, we might realize 43,400,000 tons of additional oleoresin in standing trees, an equivalent of about 290 million barrels of petroleum. These figures are interesting but have little bearing on what could be accomplished annually in the near future. During 1979, a recession year, the South harvested and processed about 26.1 million cords of pine pulpwood (Bellamy and Hutchins 1979). If our current paraquat technology had been used on these trees, the additional yield in oleoresins would have been about 2.1 billion lb.

The South has by no means reached its capacity for pine growth; on the existing forest-land base the growth and eventually the volume could be easily doubled (USDA Forest Service 1975b; Wahlenberg 1965). Indeed, the demand for southern pine pulpwood is expected to double by the year 2000 (USDA Forest Service 1975a). The opportunities for paraquat-induced oleoresin production from kraft pulpmills would increase in like manner.

Plainly, the chemically induced lightwood concept has strong potential for creating an important and expanding source of oleoresins. This forest resource is renewable. Natural stands and plantations could convert solar energy into oleoresins, under present constraints, ad infinitum. A tremendous resource base in standing timber already exists, and it is being steadily increased by wider application and greater intensity of forest management. This trend will likely continue, and cultural measures that favor pine volume growth will probably favor the oleoresin yield capabilities from paraquat treatment. These measures increase gum naval stores production (Clements 19741, and the origin of oleoresin is the same in both techniques.

### *Commercial Uses of Oleoresin, Present and Potential*

The industrial uses of turpentine and rosin are many and varied. Much of the rosin is used for chemical intermediates and in synthetic rubber, paper size, coatings, and adhesives. Turpentine is often separated into its major components--alpha- and beta-pinene. Alpha-pinene goes mainly into synthetic pine oil and insecticides, beta-pinene into adhesives and essential oils of flavorings and fragrances (Zinkel 1975b). Many former markets for oleoresin products were lost because of unstable and frequently insufficient supplies. Uncertainty of adequate supply at a reasonable price has inhibited industrial development, investment, and research in uses of this resource. If induced lightwood stabilizes and increases supply, certain old markets may be recaptured and new uses will be developed.

Some promising new uses for oleoresin products, particularly rosin, are discussed by Collier (1976, 1977), who studied the feasibility of oleoresin substitution for petrochemicals. Possible uses for rosin include alkyd, polyester, and other resins, polyurethane foams and coatings, and synthetic lubricants. Suggested uses for turpentine include isoprene, additional adhesives, terephthalic acid, and possibly motor fuel. Oleoresin-enriched trees could also be the basis for a "complete utilization" chemical industry wherein the whole tree would be processed. Silvachemicals would be extracted and other wood products such as celluloses and lignin converted to methanol or other products (Brown 1976; Szego and others 1972).

In the past the oleoresin byproducts of kraft pulpmills were not recovered for marketing or further processing; instead, they were used directly as fuel. Turpentine-supplemented fuels were used in steam-generating boilers, and resin acids (rosin constituents) were left in the spent digesting liquor, aptly termed "black liquor." After evaporative condensing, this liquor went to the recovery furnace which regained chemicals for recycling. The resin acids, along with lignin and many other substances in the black liquor, furnished the necessary combustion energy (Grantham and Ellis 1974; Koch

1972). Consequently, even when a pulpmill does not recover oleoresin, it is not wasted; it reduces the amount of fuel oil required. If the price of fuel oil continues to rise, the trend toward attaining maximum oleoresin byproduct recovery may halt, with oleoresin partially recovered and partially used as fuel. Continental Group, Inc., first became interested in paraquat-induced lightwood because of the implications in reducing fossil fuel needs of their mills. However, with the present price of oleoresins relative to fuel oil, maximum oleoresin recovery is the goal.

### *Plant Production Capacity*

What are the capabilities, and the prospects for expansion, of oleoresin production by the kraft pulpmills and wood naval stores extraction plants? For the pulpmills, additional turpentine recovery presents no serious difficulty. In some instances more condenser capacity will be required, but it has been jokingly stated that the greatest need will be simply more turpentine storage tanks.

The situation with rosin is more complex. Saponified resin acids and fatty acids are removed from black liquor by a mechanical skimmer installed in a settling tank (often called a “skim tank"). These soaps are then acidified to form crude tall oil, which contains both resin and fatty acids (Koch 1972; Zinkel 1975a). Most tall oil is now fractionated into tall oil fatty acids and resin acids (rosin). United States fractionating capacity is about 1 million tons per year, while production is about 800,000 tons (Zinkel 1975a). To take advantage of the additional resin acids in chemically induced lightwood, most pulpmills would have to increase skim tank and fractionating capacity, and also make other capital investments.

Wood naval stores plants would have to process a greater volume of paraquat-induced lightwood to achieve production comparable to that with natural lightwood, because paraquat-treated material is going to contain both lightwood and unenriched sapwood, and pound for pound less oleoresin. Other modifications would no doubt also be needed. In the South this industry will soon have to rely on chemically induced lightwood as a source of raw material or be forced out of production.

## PHYSIOLOGY OF LIGHTWOOD PRODUCTION

### *Translocation of Paraquat*

Paraquat solution is usually applied to the zylem of pine trees by spraying it on an exposed surface or placing it into open cuts or drill holes. Paraquat sprayed on the zylem surface must diffuse into the zylem and enter the tracheids before it can be transported upward in the transpiration stream. When cuts and drill holes are made in the zylem, some of the tracheids are severed, breaking the transpiration stream and allowing air to enter the tracheids. When the paraquat solution is added, the time required to re-establish the water column may delay effective movement in the transpiration stream. Most of the movement of paraquat is in the transpiration stream and therefore is upward.

Brown and Nix (1975) found that paraquat applied to the zylem surface of slash pine trees moved at 1/100 the velocity of water in the transpiration stream. They attributed this slow movement to the strong adsorption of the highly polar paraquat cation to the cellulose cell walls. With continued flow of water the paraquat cations slowly moved within the transpiration stream by repeated adsorption and desorption, similar to movement of compounds along a chromatographic column. Massive treatment with 45 ml of 8 percent paraquat per tree, applied by placing saturated cellulose fiber pads on exposed zylem surface, overloaded the adsorption sites causing large quantities of paraquat to move rapidly to the crown. All the trees were killed within 30 days. With normal rates (4 ml of 8 percent), paraquat moved 12 in. per day vertically and 0.2 in. per day radially. Davis and Carrodus (1978) suggested that some of the paraquat movement in Monterey pine (*Pinus radiata* D. Don) is associated with the trailing edge of water in the transpiration stream as water columns are broken when ray cells, whose energy is necessary for their integrity, are destroyed.

In 2-year-old loblolly pine seedlings, Schwarz and others (1977) found that most of the paraquat moves only a short distance. Even after 30 days, most of the paraquat applied to miniature bark streaks was from 0.4 in. below to 1.2 in. above the area of application,, Low concentrations of paraquat moved to the needles and caused toxic effects in them.

It is fortuitous that paraquat is translocated primarily by the transpiration stream, at a slow rate that eventually becomes negligible; paraquat ion concentrations decrease geometrically above the application site. If paraquat, like many herbicides, moved rapidly to the crown and downward in the phloem to the roots, very little resinosis could occur before the tree was killed or baldly injured. Consequently, lightwood formation and enhancement are possible only because of the translocation characteristics of paraquat.

Indirect evidence seems to indicate, however, that the rate and quantity of para.quat translocation vary greatly even in genetically identical material (Wolter and Zinkel 1976). Visual observations confirmed by analysis of wood samples show very high tree-to-tree variation in oleoresin enhancement as one progresses up the bole. Increased oleoresin accumulation extends only 4 to 6 ft above the wound site in some trees; others have oleoresin even bursting through the bark at heights of 30 ft or more. Such trees often can be found side by side and are comparable in size, vigor, crown class, age, and paraquat treatment. It seems virtually certain that this variation in resinosis is a function of variation between trees in paraquat translocation, but the causes are obscure. This phenomenon is more than interesting; it is of great practical significance. If all trees could be made to accumulate oleoresin in. quantity equal to the average for the top 30 percent of trees, oleoresin production could be more than doubled.

*Action of Paraquat*

Treatment of pine trees with paraquat causes heavy resinosis in the sapwood zylem. Near the wound site, oleoresin content of this wood may be greater than 40 percent of the water-free weight of wood compared with the usual content of approximately 2 percent (Roberts and others 1973). Resinosis develops in a characteristic pattern following radial lines from the outer edges of the surface application to the pith. If heartwood or incipient heartwood has developed around the pith, it interrupts this pattern. New resin deposits do not form in the heartwood or the transition zone surrounding it. Resinosis is most intense at the level of application and diminishes upward and downward from this level and from the surface toward the zylem center. Resinosis usually extends upward 10 to 15 times farther than it extends downward from the area of application.

Working with 8-year-old slash pine trees, Birchem and Brown (1979) reported that oleoresin moved from parenchyma and epithelial cells centrifugally through half-bordered pits into the lumens of adjacent tracheids. When the tracheids were filled, the secondary cell walls also were 'impregnated with oleoresin. Miniutti (1977) also reported a pattern of oleoresin deposit in tracheids which indicated it entered from ray parenchyma cells through half-bordered pits. On the fringes of areas with resinosis, the summerwood tracheids were usually filled with oleoresin, but in the same area the lumens of the springwood tracheids appeared to be free of oleoresin.

In addition to resinosis, paraquat treatment causes many changes in the living parenchyma cells of the zylem including: (1) increased membrane permeability, (2) disruption of cellular organization, and (3) eventually destruction of cellular membranes and organelles including the nucleus (Birchem and Brown 1979; Brown 1975).

In 5-year-old slash pine trees, Brown and others (1976) found that starch disappeared from cells near the point of entrance of paraquat into the stem. This phenomenon was accompanied by increased synthesis of oleoresin and free fatty acids. Stored food reserves were mobilized, followed by a gradual lysis of the cytoplasm and enclosed organelles. They reported that the carbon from the mobilized food reserves was shunted into the terpenoid synthetic pathway before the death of the cells, thus contributing to the rapid production of oleoresin and its release into the tracheids.

In cell suspension cultures, similar destruction of membranes and disorganization of the cytoplasm and organelles takes place, but no oleoresin is produced (Birchem and Brown 1979; Brown 1975). Cell division stopped quickly in suspension cultures placed in 1 part per million paraquat and respiration increased initially, then dropped.

Finnerty and others (1976) found that soluble carbohydrates decreased and amino acids, keto acids, resin acids, and thiobarbituric acid-reacting substances increased in 5-year-old slash pines treated with 10 ml of 0.02 percent paraquat. Schwarz and others (1977) observed decreases in starch, tannins, and lipids accompanying heavy accumulation of oleoresin in paraquat-affected areas of loblolly pine seedlings.

Ryan and Schwarz (1979) and Wolter and Zinkel (1976) reported decreased photosynthesis in seedlings after paraquat treatment and indicated that the immediate carbon source for oleoresin synthesis must come from previously fixed carbon and not current photosynthate. Defoliation experiments by Brown and others (1979) show that some but not all oleoresin in paraquat-treated trees is produced from current photosynthate since defoliation reduced oleoresin production. By making saw cuts above and below the paraquat-treated area, they also showed that oleoresin precursors are normally transported in the tree stem. Saw cuts (IO in.) above and below significantly reduced resin soaking in the treated area.

The herbicidal effect of paraquat at the cellular level involves the reduction of the paraquat cation to a stable but very active free radical, which reacts with oxygen to form hydrogen peroxide or hydroxyl radicals with the paraquat free radicals being oxidized back to paraquat cations. The paraquat is not destroyed in the process but acts essentially as a catalyst for the formation of hydrogen peroxide or hydroxyl radicals by repeated recycling of the process (Calderbank 1968). Schwarz and Ryan (1980) indicated that a superoxide, which is very active in cell destruction, may be formed directly or through production of hydrogen peroxide. The hydrogen peroxide, hydroxyl radicals, or superoxides can peroxidize lipids in the membranes of cell and cellular organelles to produce lower molecular weight products, cause the characteristic changes in membrane permeability and integrity, and finally the complete disruption of cells.

In green plants the reduction potential for reducing paraquat comes from ferrodoxins in photosystem 1 of photosynthesis (Calderbank 1968). In nonphotosynthetic tissue, such as parenchyma cells of zylem in pine tree stems, the reduction potential probably comes from the electron transport system of mitochondrial respiration as suggested by Harris and Dodge (1972) for dark-germinated flax seed.

In lightwood formation, paraquat apparently acts as a catalyst to form oxidizing compounds that disrupt the cellular structure of the living zylem parenchyma cells. This action releases sugars, fatty acids, and amino acids that act as precursors for production of oleoresin constituents. Enzymes, which control synthesis of the oleoresin constituents, are apparently released in the same process or their production is stimulated by auxins produced in response to wounding by paraquat. Ethylene, whose production is normally stimulated by wounding plants, may be involved in stimulating enzyme activity.

## OBJECTIVES OF STUDIES

The general objective of the studies on lightwood induction summarized in this paper has been to ascertain the feasibility of producing and processing chemically induced lightwood on a commercial scale. Data were gathered and evaluated for both woodlands operations and processing plants. Specific objectives were (1) Determine oleoresin yield as influenced by treatment factors and processing. (2) Assess insect pest hazards by treatment and tree species, and devise pest control measures. (3) Estimate wood growth loss due to paraquat treatment. (4) Appraise the quality of oleoresin from induced lightwood. (5) Uncover and solve technical problems in woodland and processing plants. (6) Estimate costs in dollars, and evaluate profit potential. (7) Determine environmental impact and safety, especially in reference to attaining EPA registration of paraquat for lightwood induction purposes.

To assist in meeting these objectives through cooperative studies, to reduce duplication in research efforts, and to disseminate results promptly, the Lightwood Research Coordinating Council was formed in 1974 and is now part of the Pulp Chemicals Association. Its original membership included private industry, universities, State and Federal forest services, and other public agencies. The majority of studies summarized herein were published in the proceedings of this group.

## A WORD ABOUT METHODS

There has been a multitude of tests with paraquat for evaluating lightwood stimulation--several hundred of them--but not a great many well-designed studies that also had provision for adequate sampling. There are several reasons for this, the principal one being that factional studies in paraquat research (and forestry in general) that have more than a few variables soon get logistically out of hand. Compounding this for paraquat research, it was soon discovered that treated trees within a plot varied a great deal in their lightwood-forming response. In sampling for oleoresin production, Stubbs (1978) determined that about 30 trees in each treatment plot had to be sampled to achieve a 95 percent level of confidence for the mean--a confidence interval of 10 percent. Using another approach that did not employ population variance, Pombo and Propst (1979) concluded that 50-tree sampling was required. Their approach gave no information on the confidence limits to be expected but may have been suitable for their objectives. Few researchers or groups had the wherewithal, financial and otherwise, to do this sort of sampling or the consequent laboratory analyses for oleoresins, which could amount to thousands of determinations.

This disagreeable reality was often either ignored or not acted on because the resulting sampling load was impracticable, as in Marton and Marton (1976). Another approach was to limit sampling to only that necessary to determine relative differences between treatments, as in sampling only the basal 5 to 10 ft of trees. However, the consequence of both of these approaches is that accurate data on total oleoresin yields are quite scarce.

Confidence limits of 10 percent or more associated with useful oleoresin yield data may cause some concern. Furthermore, these confidence intervals only inform us about the precision of the sampling, not the true accuracy in estimating the actual population average (measurements with a yardstick that is not 3 ft long can give very satisfactory confidence limits). All experiments had some bias of this kind--in the sample collection methodology, in preparation, and in the actual laboratory analyses. Most workers used Shepard's (1975) method, or modifications of it, for resin acid determinations. Using titration, the quantity of all free acids in the sample solution is measured; most of these are resin acids but some are not, thus the method overestimates slightly. Turpentine analyses have usually slightly. Turpentine analyses have usually followed the Pulp Chemicals Association method as given by Drew and others (1971), which can present problems, especially with small samples from wood with a low level of turpentine. The modification developed by Munson (1979), used in many of the studies conducted by the authors, overcame many of these problems but yielded values 5 percent too high. This bias fortunately was consistent and could be easily corrected. For practical use in forest stands, estimation of oleoresin content from a sample of trees is not the only source of error. That estimate must then be applied to cruise data and volume tables, which also contain error. The best of volume tables are often off by 4 or 5 percent for a particular stand. Therefore --returning to whether 10 percent confidence limits of oleoresin yield are sufficiently exact--getting more precision through even more intensive sampling and supposing one has a more accurate and useful estimate is largely an illusion. Also, estimation only needs to be sufficiently accurate to meet the needs of decisionmaking. If a rational choice can be made with estimates of no better than 10 percent accuracy, and additional accuracy would cause no change in decision, it is a waste of money to invest in estimates with 5 percent accuracy.

As an example of tree sampling, the methods used by Stubbs and Outcalt (1982) are typical and may be instructive. Trees for oleoresin determination were randomly chosen. In virtually all studies, 30 trees were destructively sampled for each treatment at each sampling date. The diameters of selected trees were measured and then trees were felled. Once cut, the total height, distance to the live crown, and distance to a 4-in. top (diameter outside bark) were measured. Then 0.75-in-thick disks were cut at I-ft intervals for the first 10 ft of bole and at 2-ft intervals thereafter to a 4-in. top (fig. 1). After the disks were debarked in the field, their diameters at 0 and 10 ft were measured. Disks 1 through 5 were put in a polyethylene bag, disks 6 through 10 in another, and the remainder in a third bag. Sample bags were packed in cardboard boxes and transported to a freezer for storage.

These samples were shipped frozen to our laboratory in Olustee, Fla., for analysis. There the sample disks were chipped, the' chips were mixed, and subsamples were drawn. Part of the sample was analyzed to determine the quantity of resin acids by using Shepard's (1975) procedure. Another part of the sample was analyzed for the quantity and constituents of turpentine by methods developed at the Olustee laboratory (Munson 1979).

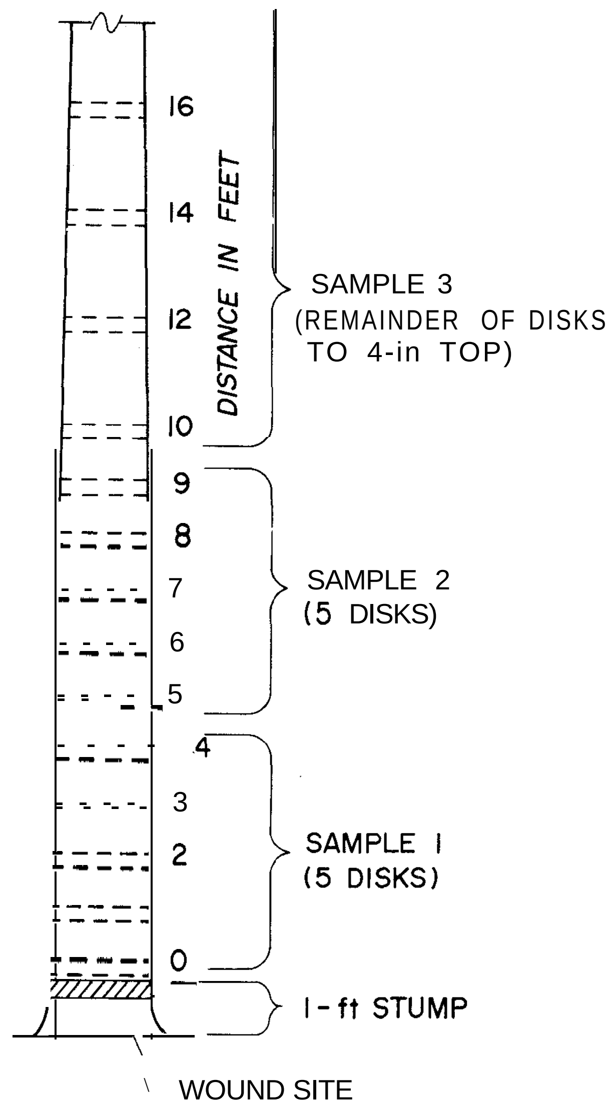


Figure 1.--Cutting diagram for collection of wood samples used in oleoresin analysis.

## RESULTS AND DISCUSSION

### *Treatment variables*

#### Species of Pine

All southern pines have been shown to form lightwood after paraquat treatment (Peters and Roberts 1976). Loblolly and slash pines have the most potential for industrial use of lightwood technology because they occupy the most area and have the largest standing volumes. Of the two, there is 1.6 times more volume in loblolly pine than in slash and longleaf pines combined, and 4.4 times as much as in longleaf. Slash pine, however, has a generally higher normal oleoresin content than has loblolly pine, and shows more response to paraquat treatment. Consequently, of the southern pines, slash pine has received the most attention in paraquat research, followed by loblolly pine, with longleaf pine a distant third. The rest of the southern pines have been subjected to little more than an initial test or a few exploratory studies. To our knowledge, no studies have been designed specifically to compare response between species. However, when slash and loblolly pines were both injected with 2 percent paraquat during the summer (Stubbs and Outcalt 1982), the gain in oleoresin content after 12 months was 0.89 lb/ft$^3$ for slash pine and 0.45 lb/ft$^3$ for loblolly (see tables 11 and 14). This greater response by slash pine has been general throughout the South. The two species also differ in the effect of paraquat treatment on turpentine constituents.

For paraquat treatment, the slash pine belt and the more northerly zone, where loblolly generally dominates, form two quite distinct entities. For practical purposes, longleaf pine can be considered with slash pine. These two regions differ in oleoresin enhancement yields, probably in effects of season of treatment, and they assuredly differ in the degree of bark beetle hazard associated with paraquat treatment. In the future when more research results are available, it might be well to prepare separate information summaries for these two major species and general regions,

**Age** of **treated pines**

Pulpwood-size pines are the obvious choice for pa.raquat treatment, whether the wood is to go to pulpmills at the end of a normal pulpwood rotation, or to wood naval stores extraction plants. Trees of sawtimber size can he more profitably utilized for lumber and veneer. The age of pulpwood-size pines will range from 15 to 30 years or so, depending upon the site quality, stocking of the stand, and other factors.

Information is limited concerning the effect of tree age on response to paraquat treatment. In preliminary tests with loblolly pine, Stubbs and Outcalt (1982) show that trees as young as 9 years old will form lightwood when treated with paraquat. Mortality, however, can result from paraquat reaching the crowns of pines 9 to 12 years old. Death caused directly by paraquat is primarily a function of tree height; therefore, pines should be at least 30'ft tall before paraquat is applied. Because trees older than 12 years generally exceed 30 ft in height, mortality caused by paraquat toxicity is not a problem.

Although it is not economically sound to treat older trees of sawtimber size, it has been hypothesized that such trees are better able to withstand the stress caused by paraquat application. The reasoning is based on circumference being directly proportional to diameter, while basal area (cross section) and bole volume are proportional to diameter squared. In comparing 1/3-circumference treatments on a large pine and on a small pine, the larger tree has a greater volume of wood for transpiration stream flow per unit length of wound and paraquat absorption site. This assists the larger tree directly and also leads to greater dilution of the paraquat. In actual practice the above does not seem to be very important, although mortality from insects attracted to paraquat-treated trees is inversely correlated with diameter (Ericksen 1978; Outcalt and Stubbs 1979). Paraquat treatments severe enough to cause problems, as evidenced by heavy insect attack and subsequent tree mortality, are more than sufficient to overide any advantage of larger tree size and generally greater age.

## Methods of Applying Paraquat

The chemical must reach live tissue within the tree to induce lightwood formation; therefore, trees must be wounded in some manner in order to apply the chemical. Of the many wounding methods tested, one of the oldest and most common is the "bark streak," a term from gum naval stores operations. Bark streaks are made by removing a l-in-high section of bark, horizontally around the tree at stump height, generally for one-third of the tree's circumference. With slash pine, 1/3-circumference bark streaks were tested by Bailey (1976), Barker and Schmid (1976), Beers (1975), Conley and Bailey (1977), Conley and others (1976), Hertel and Williams (1975), Joyce and others (1977), Roberts (1976), Roberts (1978b), Roberts and Peters (1976), Roberts and Peters (1977), and Squillace (1975). The same wounding treatment was applied to loblolly pine by Beers (1975), Conley and others (1976), Marton (1975), Roberts (1978b), and Stubbs (1978). Enos and others (1978), Hertel and Williams (1975), and Nix (1976) tested 1/2-circumference bark streaks on slash pine; Enos and others, and Nix, also tested them on loblolly pine. Bark streaks 1 in. in height have been the rule, but Roberts and Peters (1977) compared streak heights of 1, 2, and 4 in. on slash pine,, and Roberts (1979b) again compared I- and 4-in. heights on that species.

Bark-streak wounds have been the most popular method used, featuring simplicity, rapidity and thus economy, amenability for mechanization, good results in oleoresin enhancement, and, if limited to 1/3-circumference, less hazard from bark beetles than most other treatments. Bark streaks in excess of 1/3-circumference do not produce enough additional oleoresin to offset the added stress they cause the tree, and thus the higher risk from bark beetles. And streaks 2 or 4 in. high have shown no advantage in oleoresin yield.

Therefore, we recommend l-in-high bark streaks, not to exceed one-third of the tree's circumference. This is probably the most universally useful method of any tested, although, as discussed later, tree injectors have certain advantages and drill holes are highly useful for specialized purposes. These three general methods have proved to be the most useful. Bark streaks can be made by hand with a bark hack (a gum naval stores tool), or with a powered chipping saw (Clements and McReynolds 1977). More recently a cutting head mounted on a small-track vehicle has been devised for treating trees in this manner (Mappin and Propst 1979).

Ax frills, with or without herbicide application, were in early use as a means of killing trees. This wounding method has been used in paraquat studies by Enos and others (1978), Nix (1976, 1977), Roberts (1975), and Roberts and Peters (1976). The method is simple but little more can be said for it; it takes some skill and is extremely labor intensive.

Drill holes have received quite wide-spread testing. Holes with some downward slope are drilled tangentially into the bole of the tree, paraquat solution is placed in the holes, and then they are usually corked. Depending on the number and arrangement of holes, which in effect are a chord of some portion of the tree's circumference because they are drilled tangentially, treatment can be tailored to affect approximated 1/3-circumference, 1/2, or whatever. With slash pine, varied arrangements of holes have been tested by Enos and others (1978), Peters and Joyce (1975), Peters and Roberts (1977), Peters and others (1978, 1979), and Roberts (1979a). Enos and others (1978) also used drill holes with loblolly pine, as did Stubbs (1978). In terms of increased oleoresin, the drill holes have shown no advantage over simpler methods, such as the bark streak or tree injector, and they are at least twice as expensive (Stubbs 1978). Thus, they cannot be recommended for paraquat application except for stump treatment (described later).

A variant of the drill-hole method involves placing paraquat-impregnated wooden dowels into the hole or holes (Roberts and Peters 1977; Stubbs 1978). Or, cellulose plugs or other absorbent material can be put into holes and then saturated with paraquat solution (Enos and others 1978; Roberts 1979a; Roberts and Peters 1977). Neither version shows any particular advantage in slash or loblolly pines, and neither is recommended.

As the bark streak was borrowed from gum naval stores, so were most tree-injection methods taken directly or modified from tools and methods designed for applying herbicide to unwanted trees. One of these tools is the Punch-Hammer[1] (Crutchfield 1976a; Marton 1975), which wounds and meters chemical at the same time. According to Crutchfield (1976b), who used this tool on loblolly pine, wounds around the tree should not be spaced closer than 6 in. A second tool is the Hypo-Hatchet (Joyce 1978), which also wounds and applies in the same stroke. For paraquat treatment of large numbers of trees, neither of these tools is very suitable. They lack the paraquat solution storage capacity of tree injectors and are no easier to use.

Two devices not related to herbicide use that have been modified for use in paraquat treatments are the Med-E-Jet and grease gun. The former is used in the medical profession to inject precise dosages of innoculum through the skin by using compressed carbon dioxide as a propellant. Equipped with a needle, of which several designs have been tested, the Med-E-Jet is used in paraquat application by first forcing the needle through the bark, and then using the compressed carbon dioxide feature and metering mechanism to introduce set quantities of paraquat solution into the tree, by creating a cavity between the inner bark and zylem. Med-E-Jets so modified have been tested by Bailey (1976), Conley and Bailey (1977), Crutchfield (1976a), and Roberts (1979b); also by Drew (1976), Drew and Joyce (1975), and Joyce and others (1977) in reports pertaining to a single study. The device is fragile, ill-suited to large-scale treatment, and has produced highly variable results in oleoresin enhancement. Except as a basis for ideas in mechanization, it can be dismissed from further consideration. Roberts (1978a) utilized the high-pressure capability inherent in grease-gun design and modified one for use in paraquat injection. It will function as well as the Med-E-Jet, is easier to operate and much cheaper. In a test by Roberts (1979b) it did not appear to do as well in oleoresin enhancement as did a tree injector. With further development the tool might have some promise for small-scale operations.

Nowadays the most popular tools for deadening trees in timber stand improvement are tree injectors. Two of these, the Jim-Gem and Cran-Jector, have been used extensively in paraquat studies, including those on slash pine by Conley and Bailey (1977), Roberts (1979a, 1979b), and Stubbs (1978); on loblolly pine by Stubbs and Outcalt (1982) and Waite (1977, 1978); and on both slash and loblolly pines by Bailey (1976). Tree injectors have proved to be extremely useful tools for paraquat treatments, much the most satisfactory of all injection devices. Tree injectors and power-chipped bark streaks are presently the least expensive methods, and tree injection is somewhat less expensive than is chipping (Stubbs 1978, Stubbs and Outcalt 1982). Drew and Joyce (1979) came to the same conclusion, and gave a production rate of 2 acres of pines treated per person-day. In the class of timber they were dealing with, this amounted to something over 40 cords treated per person-day. A skilled, energetic, and strong person can maintain this rate in cooler weather if no problems are encountered. With ordinary laborers, breakdowns, and rainstorms, working all seasons day after day, Stubbs and Outcalt (1982) realized a production rate of about 26 cords per person-day (8-hour day). With careful selection of personnel, thorough training, and close supervision, a sustained production of about 35 cords per person-day could be achieved.

Use of tree injectors has the added attraction that, given nominally equivalent wounding and paraquat dosage, oleoresin enhancement is superior to the bark-streak method, the most satisfactory alternative (see Oleoresin Yields section below). However, injected trees are more prone to mortality from bark beetle attack than are trees given bark streaks (see the Insect Attack section below). Spacing of injector wounds around the base of the tree is impor-

[1]Throughout this paper, trade names are provided solely to identify chemicals and equipment used. Such mention does not constitute endorsement by the U.S. Department of Agriculture.

tant, especially in relation to beetle attack. Injector blades 1-1/2-in. wide are most commonly used, although other widths are available. With a I-l/2-in. blade, spacing on 3-in. centers around the tree gives nominal treatment to 50 percent of the circumference. But paraquat has some lateral movement from the wound, about one-quarter of an inch on each side. Thus, this spacing treats roughly two-thirds of the tree circumference--which is too much. Trees with such severe wounding can be expected to be overwhelmed by bark beetles, regardless of paraquat concentration or insecticide spray. Wound spacing with a I-l/2-in. blade should not be less than 5 in. on centers, which gives a nominal treatment of 30 percent of the tree's circumference. Spacing for other blade widths should be in proportion.

In conclusion, only two wounding methods are given general recommendation: (1) a single bark streak at stump height, 1 in. wide and extending one-third of the way around the tree circumference, and (2) use of a tree injector around the tree base, with spacing in proportion to blade width as g' -en above. For bark streaks, paraq. . solution is applied in a second operation, generally by spraying the surface of the wound until runoff. The tree injector wounds and meters paraquat solution into the wound in one operation. With slash pine, paraquat solution concentration (percent cation by weight in water) should not exceed 4 percent with the bark-streak method, and that concentration is risky. The bark beetle problem being what it is with paraquat-treated slash pine, one must be circumspect in using the tree injector with this species, and in no case should the paraquat solution concentration exceed 2 percent. North of central Georgia, the tree injector on slash pine has been satisfactory provided treatment duration did not exceed a year or so. In the main slash pine belt, the bark-streak method is preferred. For loblolly pine, paraquat concentration with the bark-streak method should not exceed 5 percent, and 2 percent is recommended with the tree injector. Paraquat concentrations will be discussed in detail in a later section.

**Multiple wounding**

In attempts to gain more oleoresin enhancement, additional wounds have been superimposed on trees at initial treatment time, or added sequentially later. In a southwide cooperative study sponsored by the Lightwood Research Coordinating Council, both slash and loblolly pines were given two treatments, one of which consisted of a 1/3-circumference bark streak at stump height and another one superimposed 3 ft higher, both sprayed with 4 percent paraquat solution. The result was unacceptable mortality from bark beetle attack, generally 25 percent or more, as reported for slash pine by Barker and Schmid (1976) and Beers (1975); for loblolly pine by Ericksen (1978) and Marton (1975); and for both slash and loblolly pines by Gill (1978). Nix (1977) treated both loblolly and slash pines with two 1/2-circumference bark-streak wounds, and reported no advantage in oleoresin yield over one bark streak. Using 1/4-circumference bark streaks, Enos and others (1978) put one on one side of the tree, another on the opposite side, and then two more above these but found little gain in oleoresin from these four 1/4-circumference bark streaks as compared with two of them. Therefore, multiple wounding can be summed up as usually hazardous and resulting in little if any additional oleoresin, certainly not enough to pay the cost of this additional treatment.

**Mechanization**

The opportunities for profitable mechanization of paraquat treatment appear to be excellent. The powered chipper (Clements and McReynolds 1977) for producing bark streaks has already been discussed. Some development was done on a cutting head for bark streaks mounted on a farm tractor (Schillings and Sanders 1975), but this work was not pursued to a satisfactory conclusion, Hercules, Inc., has two machines that employ a small front-end loader (Melroe Bobcat 722) modified with tracks for all-terrain use. For bark streaks, a custom cutting head is attached which also sprays paraquat solution to the newly cut wound. For stump treatment in their Pinex Program, Hercules, Inc., has developed a drilling head that also places paraquat solution in the holes (Fajans 1980).

### Paraquat Concentration and Amount

Tests have included virtually the entire gamut of possible paraquat solution strengths, ranging from 0.22 percent (Enos and others 1978) to 24 percent (Roberts 1976), which is the undiluted concentration as sold by the manufacturer. Evaluation of paraquat solution concentrations must include hazard of bark-beetle-caused mortality as well as oleoresin yield.

From published information it is difficult to determine the effect of paraquat concentration on yield, because of variation between tests in wounding methods, treatment durations, and other factors. Concerning slash pine, Drew (1976) applied 2 and 8 percent paraquat to 1/3-circumference bark streaks. After 12 months, the 2 percent paraquat was nearly as affective in oleoresin enhancement as the 8 percent; however, after 24 months Joyce and others (1977) reported for the same study that 8 percent paraquat was more effective in oleoresin accumulation, but 33 percent of those trees were dead. Roberts (unpublished data) tested 0.5, 2.0, 4.0, 6.0, and 8.0 percent paraquat used with either a 1/3-circumference bark streak or a tree injector (1-1/4 in. blade, wounds spaced on 4-in. centers). After 12 months, for both wounding methods the 0.5 percent paraquat concentration resulted in significantly less oleoresin yield than the rest. With the injector, 2 percent was as effective as 8 percent paraquat; however, with the bark-streak method, oleoresin yield increased with paraquat concentration. Averaging together the oleoresin data from both wounding treatments, 8 percent paraquat induced about 12 percent more oleoresin than did 2 percent. Rut this study also indicated that in order to keep insect-caused mortality below 10 percent, the tree injector should not be used with a paraquat concentration higher than 2 percent, nor should the bark streak be used with a solution concentration higher than 4 percent.

Also with slash pine, Roberts and Peters (1977) found 2 percent paraquat to be as effective as 4 percent after 12 months, and mortality was negligible with both. Peters and others (1978) compared 0.5 and 2 percent paraquat, and after 19 months found oleoresin enhancement over controls to be about 76 percent for 0.5 percent paraquat and about 104 percent for 2 percent paraquat. To determine whether severe wounding would produce practicable increases in oleoresin in 3 months without need of an insecticide spray (one half the treatment cost; Stubbs 1978), Roberts (1979b) compared paraquat concentrations 1, 2, and 4 percent. The 2 percent solution produced somewhat higher yield, but the difference over the other two concentrations was not statistically significant.

When the above information as well as other published reports is considered, the efficacy of higher strength paraquat solutions in producing additional oleoresin appears to have been overrated. All the oleoresin yields discussed here are on a whole-tree basis, while many reports in the paraquat literature give oleoresin data for only the basal 5 or 10 ft. From these latter reports it often appears that higher concentrations give higher yields for the basal sections, and they may do so, but most such comparisons are confounded by increased wounding. We know of no published information that shows paraquat concentrations of less than 2 percent, when applied to the tree bole (root treatment is another matter), to be comparable in oleoresin enhancement to 2 percent or greater concentrations, if the treatment duration extends more than 6 months. Similarly, concentrations of 6 or 8 percent may be superior to lower concentrations if treatment durations exceed 1 year. But if paraquat solutions of 6 percent or more are to be profitable, 90 percent or more of the trees have to survive. Due to the bark beetle hazard, slash pine should not be injected with paraquat concentrations higher than 2 percent; for the bark streak we recommend not more than 4 percent, and 2 percent is certainly safer.

Working with loblolly pine, Nix (1977) tested 2 and 8 percent paraquat and found the 2 percent more effective in increasing oleoresin, and it suffered less mortality. Roberts (unpublished data) applied 0.5, 2.0, 4.0, 6.0, and 8.0 percent parayuat to loblolly pine with a tree injector (I-l/4-in. blade, 4-in. centers) and on single, 1/3-circumference bark streaks. Combining results from both wounding methods, oleoresin yield data after 12 months showed a positive trend with increasing paraquat solution concentration. The 8 percent paraquat showed a 56 percent gain in yield over 0.5 percent paraquat, a 39 percent gain over 2 percent paraquat, 14 percent over 4 percent paraquat, and 9 percent over 6 percent paraquat. Tree losses to bark beetles were low at 1 or 2 percent in all the bark-streak treatments, and comparably low with the tree injector except for the 8 percent paraquat treatment. Stubbs and Outcalt (1982) also used the 1/3-circumference bark streak and a tree injector (1-1/2-in. blade and 5-in. centers) to compare 2 and 5 percent paraquat solutions on loblolly pine. Treatments were replicated in spring, summer, and fall. Overall, both concentrations performed equally well in lightwood induction (see table 10); although 5 percent paraquat showed a slight increase in oleoresin yield over 2 percent paraquat, the overall difference for all seasons combined was not statistically significant. However, in some summer treatments the 5 percent solution was superior. Bark-beetle-caused mortality was below 10 percent in all treatments (except for spring application of 5 percent paraquat with a tree injector, and no insecticide spray protection (see table 9).

The preceding studies with loblolly pine, except for Nix (1977), were conducted in the Upper Coastal Plain of South Carolina. In this region loblolly pine can be paraquat treated with no protective insecticide spray whatever, and we expect the same would hold true from about the middle of Georgia northward. When treating without an insecticide spray, paraquat concentration should not exceed 5 percent on single, 1/3-circumference bark streaks and 2 percent using tree injectors (1-1/2-in. blade and 5-in. centers). If a protective insecticide spray is applied at time of paraquat treatment, higher concentrations can be used but the additional oleoresin gained, if any, will have a value very much less than the cost of the insecticide spray.

In treating loblolly pine from central Georgia southward, spray with insecticide and limit paraquat concentrations to 5 percent on single, 1/3-circumference bark streaks and 2 percent for tree injector.

## Use of Ethrel

Efforts have been made to increase lightwood induction by mixing paraquat with other chemicals. In early tests, Ethrel (2-chloroethyl phosphonic acid) showed the most promise. Working with slash pine, Peters and Roberts (1977) added a 5 percent Ethrel solution to paraquat solutions of 0.5, 1.0, and 2.0 percent. The addition of Ethrel to paraquat increased oleoresin enhancement in what appeared to be a synergistic manner; i.e., the combination was more than additive. Wolter (1977) also reported that Ethrel alone would produce some lightering in red pine (*P. resinosa* Ait.). Continuing research on slash pine, Peters and others (1978) tested a 5 percent Ethrel solution with 0.5 percent and 2 percent paraquat, plus other treatments. Again the Ethrel appeared to interact with paraquat, and in the best treatment in terms of oleoresin yield (2 percent paraquat plus 5 percent Ethrel), the admixture of Ethrel accounted for a 30 percent increase in oleoresin accumulation. A third experiment with slash pine gave quite different results. Peters and others (1979) compared mixtures of 5, 10, and 15 percent Ethrel with 2 percent paraquat and found no significant increase in oleoresin yield attributable to Ethrel.

From the foregoing, we must conclude that the case for Ethrel-paraquat synergism with slash pine is not proven, but the addition of Ethrel will usually increase oleoresin production. More information is needed before treatments involving Ethrel can be recommended for slash pine; in all the above-mentioned research with this species the wounding treatment involved combinations of drill holes, often sequential over time. Such treatments would not he economical.

With loblolly pine, Stubbs and Outcalt (1982) tested 10 percent Ethrel solution added to 2 and 5 percent paraquat solutions. Chemicals were applied to 1/3-circumference bark streaks or injected into trees. The injector had a 1-1/2-in. blade and wounds were spaced 5 in. apart on centers. Matching treatments without Ethrel were also applied. Ethrel increased oleoresin production, with the greatest increase occurring in summer-applied treatments (see table 10). Ethrel improved yields by increasing the level of oleoresin accumulation over a greater portion of the tree, especially the second 5 ft of the bole. When the tree injector was used, Ethrel was beneficial in combination with 2 percent paraquat but not with 5 percent. With the bark streak the results were reversed, being generally better with 5 percent paraquat (see table 13).

For loblolly pine, given one 1/3-circumference bark streak, we recommend the addition of 10 percent Ethrel solution to 5 percent paraquat solution. A 5 percent paraquat concentration is too high for use with the tree injector unless an insecticide spray is given; even if Ethrel is added, this operation is not **as** profitable as using 2 percent paraquat, **a** treatment that requires no insecticide spray cost, And because Ethrel showed no benefit when added to 2 percent paraquat concentration, we do not recommend the use of Ethrel with tree injectors on loblolly pine.

## Use **of other chemicals**

Joyce and Drew (1979) tested more than 200 chemicals or combinations of chemicals, and found that none of them would induce as much oleoresin enhancement as did paraquat. They also experimented with chemicals in mixture with paraquat, of which triethylamine (TEA) was the most promising. An 8 percent solution of TEA was added to 2 percent paraquat and applied with a tree injector to slash pine. After 12 months, the yield increases over paraquat only were 36 percent more turpentine and 32 percent more resin acids. A similar experiment with loblolly pine gave increases of 35 percent more turpentine and 26 percent more resin acids. These increases exceed anything reported for Ethrel, and triethylamine should be tested further.

## Season of Treatment

Drew (1976) found that in north Florida there was little difference between summer and winter treatment of slash pine for oleoresin production. Our research in Florida and that of nearby cooperators in this region tend to substantiate this finding, but for a short-duration treatment of 3 months, Roberts (1979b) found that March (early spring) treatment produces more gain in oleoresin than does December (winter) treatment.

Farther north, however, season of treatment does appreciably affect ultimate oleoresin yield. In the Piedmont of South Carolina, oleoresin production from paraquat treatment in August (Nix 1976) was less than that from April treatment (Nix 1977). Studies by Stubbs and Outcalt (1982) on loblolly pine also show that season of treatment significantly affects oleoresin enhancement in the Upper Coastal Plain of South Carolina. Spring applications produced the best average oleoresin yields, with no difference between average yields of summer and fall treatments (table 1). Oleoresin production within the first 5 ft of the bole was equal for all seasons of treatment, but spring treatments caused a greater response in the upper portions of the stem. A significant interaction was found between season of treatment and wounding method. Superiority of the tree injector over the bark streak decreased from spring to summer to fall (see table 10).

Spring is also the time of greatest hazard from bark beetle attacks, both in the slash pine belt and in the loblolly pine dominated regions farther north. We have taken this into consideration, however, in the treatment recommendations we have given in previous sections of this paper, and thus prescriptions by season as related to bark beetle hazard will not be given.

Table 1.--Average oleoresin content of loblolly pine 1 year after treatment with 2 or 5 percent paraquat, by season of treatment

| Tree section | Spring | Summer | Fall |
|---|---|---|---|
| | *Percent of dry weiyht* | | |
| 0-5 ft | 8.72a | 8.38a | 8.61a |
| 5-10 ft | 4.60a | 4.01ab | 3.70b |
| 10 ft to 4-in. top | 2.40a | 2.28ab | 2.14b |
| Total stem | 4.36a | 3.65b | 3.83b |

Values followed by the same letter within rows are not significantly different at *P = 0.05.*

Treatment Duration

Preliminary evidence for slash pine indicated that about 80 percent of all the oleoresin to be expected from a single paraquat application accumulates within 11 months after treatment. More recent data for slash pine, however, show a linear increase for up to 17 or 18 months (Drew 1976; Hurley and others 1977; Joyce and others 1977) and then an actual decrease in oleoresin content at 24 months. The latter may well be an artifact of sampling. Enos and others (1978) for slash pine show a fairly steady increase in oleoresin through 20 months. A study of slash pine by Stubbs and Outcalt (1982) showed an overall linear increase in oleoresin accumulation throughout the study duration of 22 months (fig. 2).

For loblolly pine, Stubbs and Outcalt (1982) found that oleoresin content increased over time, but that the change was not linear. All of the loblolly data show a decrease in the rate of lightwood formation at some time during the study (figs. 3 and 8). It is unlikely that the oleoresin content actually decreased as some of these data indicate. It is more probable that the accumulation leveled off, with the apparent decrease due to random variation in samples.

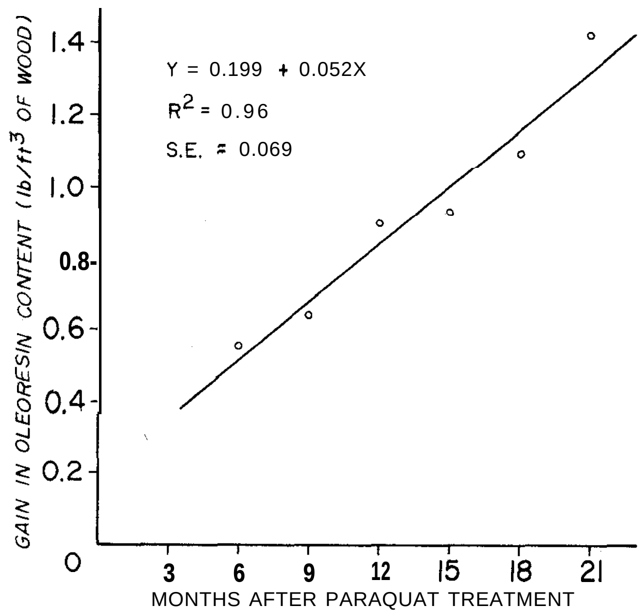


Figure 2.--Additional oleoresin resulting from tree-injector applied, 2 percent paraquat treatment of slash pine.

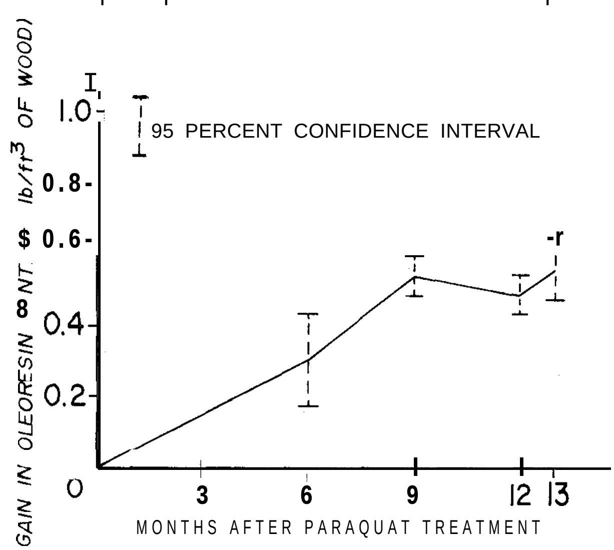


Figure 3.--Additional yields of oleoresin from loblolly pine after a 1/3-circumference bark streak, 5 percent paraquat treatment.

These loblolly pine data show an initial increase in oleoresin formation, then a leveling off with little change at approximately 12 through 18 months after treatment, followed by a second surge in accumulation. Slash pine shows a similar pattern, but less pronounced (see fig. 2). This period of reduced lightwood formation does not appear to be a seasonal effect, because it occurred during the summer in the slash pine study and in the fall or dormant period in the loblolly studies.

Severity of treatment can affect the pattern of oleoresin production over time. Trees treated by Stubbs and Outcalt (1982) with two dowels had reached virtually maximum oleoresin content after 8 months, and this level was maintained with little variation through 21 months (fig. 4). All the other treatments showed some increase in oleoresin accumulation, 12 months compared to 21 months after treatment (figs. 2 and 8), although the rate of increase varied. This extreme treatment using two dowels per tree is not recommended in any case, because of high tree-mortality rates.

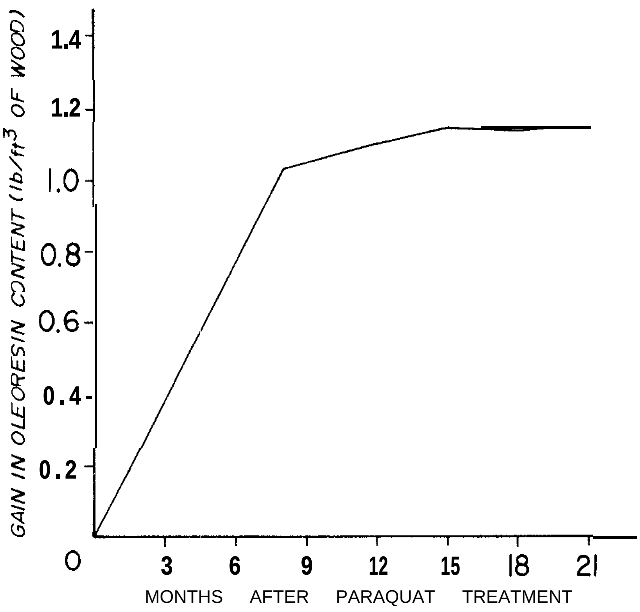


Figure 4.--Additional oleoresin content of loblolly pine resulting from a double-dowel paraquat treatment.

It appears that treatment duration for slash pine can extend for 18 months or more, if the bark beetles allow, with a steady increase in oleoresin yield over time. For loblolly pine, these data show little reason for extending treatment beyond 1 year.

*Treatments to Produce Lightwood in Stumps*

Hercules,, Inc., scientists have applied a variety of solution concentration by several methods (Enos and others 1978). Their success with low concentrations of paraquat and interest in utilizing the stumps that are left after tree harvest led them to the development of the "Hercules Pinex" treatment. This treatment involves drilling two parallel downward-sloping holes from the root collar into the taproot of pine trees and filling the holes with a dilute solution of paraquat (Fajans 1980) .

Two years after treatment, Brown and Pienaar (1981) found that 0.25 percent paraquat solution applied in two 1/2-in-diameter holes did not significantly affect tree growth, but 0.5 percent paraquat applied to one 1/2-in-diameter hole reduced volume growth by 13 percent. The 0.25 percent paraquat treatment increased oleoresin content of the stump and taproot by 4.3 times and that in the first 4-ft bolt of the stem by 1.4 times. Observed insect attacks were considered to be comparable to what would be expected in trees worked for gum naval stores.

Preliminary studies now in progress by USDA Forest Service scientists (unpublished information) in cooperation with Reichhold Chemicals, Inc., and Owens-Illinois Corp. showed that resin acids content of the stump and taproot of slash pines was increased by drilling two parallel downward-sloping holes in the taproot and filling them with paraquat concentrations ranging from 0.05 to 0.5 percent. One year after treatment (fig. 5), the lowest paraquat concentration tested, 0.05 percent, increased resin acids in the stump and taproot by 4.8 times. Further increase in paraquat concentration caused a moderate increase in resin acids, and then a decline. In the lowest 5-ft bolt of the stem, resin acids showed a continuous but diminishing increase as paraquat concentration increased. Black turpentine beetle attacks and tree mortality increased as paraquat concentration increased (fig. 6). Paraquat concentrations should be kept below 0.1 percent to minimize tree mortality and the invasion of lightwood streaks into the merchantable tree stem.

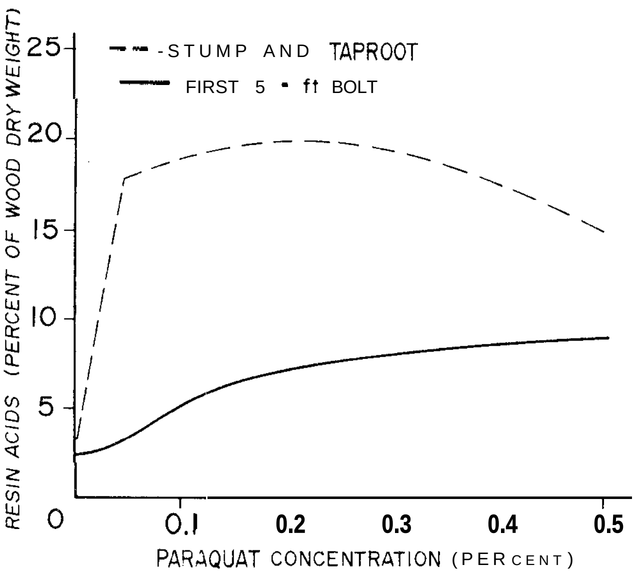


Figure 5.--Effect of paraquat concentration on resin-acids increase after treatment of slash pine taproots and lower bole.

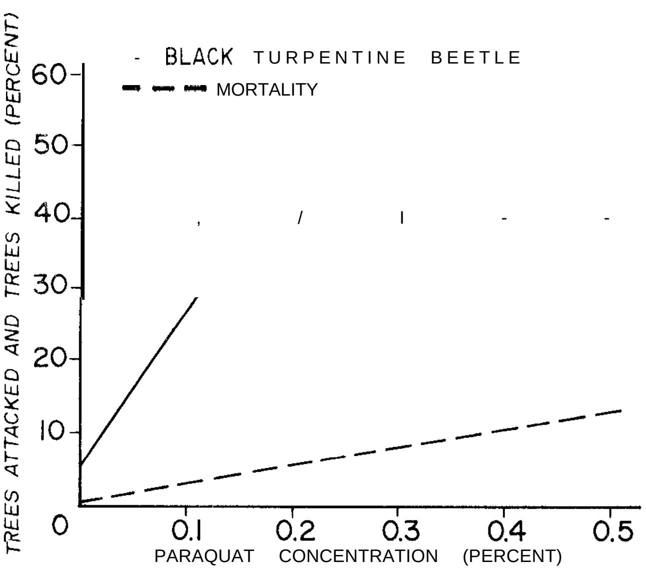


Figure 6.--Tree mortality and black turpentine beetle attack as related to paraquat concentration used in drill holes in slash pine taproots.

*Insect Attack and Tree Mortality in Paraquat-Treated Stands*

Since the discovery that paraquat would induce lightwood formation in southern pines, one of the major concerns has been bark beetle attacks on treated trees. An increased level of bark beetle attack has been noted in most of the paraquat research studies conducted in the South. In order of importance, mortality losses have been caused by engraver (*Ips* spp.), southern pine (*Dendroctonus frontalis* Zimm.), and black turpentine beetles (*D. terebrans* Olivier). Secondary insects, principally ambrosia beetles (*Platypus* spp.), have attacked dying trees but have seldom caused mortality.

Slash pine has proved to be more susceptible to bark-beetle-caused mortality than has loblolly pine. Studies involving slash pine will be discussed first, beginning with those that report heavy losses. After treating with 8 percent paraquat on a 1/3-circumference bark streak, Joyce and others (1977) reported that mortality reached 33 percent after 24 months. The trees were sprayed four times with a BHC solution. Gill (1978) used the same treatment and had 26 percent loss after 18 months among trees sprayed with 1 percent lindane. Use of 1/2-circumference frills resulted in heavy mortality even though the paraquat concentrations used were 1.66 percent and less (Enos and others 1978). These trees had received a 1 percent spray of BHC. In a 19-year-old overstocked plantation, Roberts (1979a) applied 2 percent paraquat by two methods and observed heavy mortality after 12 months. The tree injector method with wounds spaced on 4-in. centers resulted in 58 percent of the trees dying, but even the 1/3-circumference bark-streak method caused 25 percent mortality. The trees had received a 1 percent BHC spray.

Among studies reporting moderate losses is Draper's (1978), in which, after 18 months, 8 percent paraquat applied to a 1/3-circumference bark streak resulted in mortality of 13 percent in a 15-year-old stand and 3 percent in a 24-year-old stand. Both stands were sprayed repeatedly with lindane. Outcalt and Stubbs (1979) used 2 percent paraquat with a tree injector at 5-in. centers, and a 1 percent BHC spray. Mortality was about 4 percent after 10 months and rose to 13 percent at 15 months.

In addition, there have been some studies where negligible or no losses occurred, as in the Second LRCC Southwide Study. Two percent paraquat was applied to a 1/3-circumference bark streak, trees were sprayed to a height of 3 ft with 1 percent BHC or lindane, and the treatment duration was 9 months. Five months after treatment, Overgaard and others (1977) found 38 percent of the trees had been attacked by *Ips* spp., but no mortality. After 9 months, Roberts (1978a) confirmed that mortality had been negligible. In a study employing the tree injector and a good many other experimental wounding methods, all with 2 or 4 percent paraquat, Roberts and Peters (1977) found that the tree injector invited the most insect attack, but after 12 months only 2 of the 430 trees in the study had died. Finally, Peters and others (1978) reported low mortality after 19 months in a study using 0.5 or 2 percent paraquat placed in drill holes.

Loblolly pine in general is less susceptible than slash pine to beetle-caused mortality after paraquat treatment. However, all the authors have had loblolly pine studies where the limits of wounding severity were overstepped, and the resulting mortality from bark beetles was heavy. Others have had similar experiences. In southern Alabama, Waite (1977) applied 8 percent paraquat in summer with a tree injector on 3-in. centers, and sprayed with BHC. In a brief time, attack by *Ips* beetles was heavy, and the trees had to be cut after 2 months. In a second study Waite (1978) reduced the paraquat concentration to 4 percent and treated the trees in winter. This study was to have extended for 9 months, but the trees had to be cut at 6 months. *Ips* beetles again. Nix (1977) reported heavy losses after applying 8 percent paraquat to either a 1/2-circumference bark streak or an ax frill, first in April with a second treatment in July. Gill (1978) treated loblolly pine with 8 percent paraquat on a 1/3-circumference bark streak and reported 19 percent tree mortality after 18 months. After the same treatment, Ericksen (1978) encountered 19 percent mortality in a 24-year-old stand but no mortality in a stand 13 years old.

Treatments causing very low losses are also frequently reported, as in Enos and others (1978), who treated loblolly pine with 1.66 percent paraquat applied to a 1/2-circumference ax frill. Also, Moore (1977) and Outcalt and Stubbs (1979) experienced negligible losses after spraying 2 or 5 percent paraquat onto single, 1/3-circumference bark streaks. In another study, 2 or 5 percent paraquat with and without Ethrel was applied with either a 1/3-circumference bark streak or a tree injector on 5-in. centers. Tests were made in the spring, summer, and fall; also, one-half of the trees were sprayed with insecticide and the rest were not sprayed. Most treatments had very light mortality after 6 months (Moore and others 1979) and 12 months (Stubbs and Outcalt 1982).

From questionnaires sent out on two occasions to those conducting studies of lightwood induction with paraquat, Drew (1977, 1978) prepared two summary papers giving overviews of the insect pest situation. In his 1977 paper, Drew reported that *Ips* beetles were the most important pests, especially on slash pine. No insecticide, concentration of insecticide, or spray method was totally effective. Paraquat concentration, not the dosage or amount per tree, is correlated with insect attack; concentrations higher than 4 percent are too much for use with slash pine, and 5 percent should not be exceeded with loblolly pine. Of application methods, tree injectors invited more attack than bark streaks, and the more severe the wound the greater the attacks. Spring treatments are likely to have the highest rates of insect attack, and fall treatments the lowest. There appeared to be a positive correlation between oleoresin enhancement and severity of beetle attack; however, virtually all these oleoresin data were for basal sections and were not on a whole-tree basis. Drew's survey of 1978 strengthened what were essentially the same conclusions.

To keep mortality at a low level, the common thread that runs through the previous discussions is evident: (1) With slash pine, do not use paraquat concentrations that are higher than 4 percent with a bark streak or 2 percent with a tree injector. (2) With loblolly pine, the limits are 5 percent paraquat for bark streaks and 2 percent for tree injectors. (3) Any wounding that affects more than one-third of the tree's circumference is too much. (4) In general, longer treatment durations mean more risk of mortality from bark beetles. (5) Neither an initial insecticide spray nor repeated spraying is to much avail if the paraquat treatment is too severe, either in paraquat concentration or wounding. (It should be mentioned that only the basal 10 ft or less is sprayed,, usually 3 or 6 ft. (6) Do not treat stands with low tree vigor.

There has been some concern that beetle populations might build up in treated trees and then attack surrounding trees, causing severe losses. No such attacks have occurred in any study reported, and there is no evidence whatever that this will happen. Furthermore, even when heavily attacked trees given severe treatments were adjacent to less severely treated trees, there has been no evidence of a significant spread of beetles from the heavily attacked trees. Thus, it appears there is little threat of beetles causing any significant mortality in adjoining stands (Clark 1979; Drew 1977, 1978; Hertel and others 1977).

## Degree of Hazard and Control of Insect Pests

The insect problems associated with paraquat-induced resinosis soon attracted the help and interest of entomologists, who began to assess the problem and then attempted to devise adequate control measures. In a series of experiments, Hertel and others (1977) treated slash pine in north Florida in the winter (January), spring (April), summer (July), and fall (November) with 8 percent paraquat applied to single, 1/3-circumference bark streaks. All trees were sprayed with 1 percent RHC to a height of 3 ft. Only the winter treatment had an acceptable level of survival --about 93 percent--and they were lucky as we now know. In a study of wounding intensity installed in summer, they tested 1/3-, 1/2-, and 2/3-circumference bark streaks plus two superimposed 1/3-circumference bark streaks, all with 4 percent or 2 percent paraquat. Half the trees received a 1 percent lindane spray to a height of 3 ft and the other half did not. With 4 percent paraquat, the 1/3-circumference wound plus lindane spray had the lowest mortality, 10 percent. With 2 percent paraquat plus lindane spray, mortality was 10 percent or zero with l/3-, 1/2-, and even 2/3-circumference treatments (there were but 10 trees per treatment, and one dead tree gave 10 percent mortality). Mortality was severe in all treatments without lindane spray; they concluded that this spray was a necessity, and subsequent experience has verified this conclusion for slash pine. To further test paraquat concentration effect, 2 percent was compared with 8 percent on trees wounded in the summer with single, 1/3-circumference bark streaks. On trees given a 1 percent lindane spray, mortality was 50 percent for the 8 percent paraquat after 18 months, but zero for the 2 percent paraquat. Their general conclusions were: (1) Trees must be sprayed with insecticide. (2) Spring is the worst time to treat with paraquat, winter the least hazardous. (3) Wounds should not exceed 1/3-circumference with 4 percent paraquat. (4) Paraquat concentration should not be higher than 4 percent.

Merkel and Clark (1981) tested a number of insecticides, including lindane, at concentrations of 1 and 2 percent sprayed to heights of 3 or 10 ft. Slash pines in north Florida were treated in spring, summer, fall, and winter with 4 percent paraquat using 1/3-circumference wounding. Half the trees were sprayed; the others were left unsprayed. After 12 months, lindane proved to be much the best insecticide and spraying proved to be necessary. However, in the spring treatment, mortality was 40 percent or more no matter which spray was used. In general, 1 percent lindane gave as good protection as 2 percent, and spraying to a 3 ft height was as effective as spraying to 10 ft.

Tests of other insecticides compared with BHC or lindane have also been made by Merkel (1979), Moore (1977), and Williams (1979). In all instances, BHC or lindane was the most effective in reducing bark beetle attack.

The entomological studies we have discussed in some detail all concerned slash pine in north Florida. In what follows, quite different results were obtained in the Upper Coastal Plain of South Carolina, primarily with lohlolly pine. In a series of studies there, the southern pine beetle population was low, and black turpentine beetle attacks on paraquat-treated trees caused negligible mortality. *Ips* beetles were the primary insect pests and accounted for virtually all of the insect-caused tree mortality.

## Effect of paraquat treatment, season, and insecticide

On plots of 20 trees each, Moore (1977) applied one of four paraquat treatments: (1) 1/3-circumference bark streak (wound only), (2) 1/3-circumference bark streak with 5 percent paraquat, (3) 1/3-circumference bark streak with 2 percent paraquat and insecticide, and (4) 1/3-circumference bark streak with 5 percent paraquat and insecticide. These treatments were replicated with three different insecticide sprays--BHC, Reldan (chlorpyrifos-methyl), and Dursban (chlorpyrifos) at two levels each, sprayed on the tree boles to a height of 12 ft. All treatment combinations were applied in spring, summer, and fall to loblolly pine plantations at each of three locations on the Savannah River Plant (DOE), near Aiken, S. C.

Reporting results of this study, Outcalt and Stubbs (1979) noted that even though season and length of treatment are confounded, season of treatment did not significantly influence tree mortality (table 2). Also, because these data show additional mortality with longer treatment duration, we would expect average mortality by season to be even more equivalent if all seasonal replications reached 28 months. Only the 5 percent paraquat treatment without insecticide had significantly higher mortality (3.8 percent) than the control, but mortality was not significantly reduced when this paraquat treatment was used with an insecticide. Thus, prophylactic spraying of insecticide immediately after paraquat treatment, which accounts for approximately half of the total treatment cost (Stubbs 1978), certainly would not pay in this case. Because use of insecticide did not affect mortality, it is not surprising that there was no difference in tree mortality by insecticide type.

Table 2.--Mortality of paraquat-treated loblolly pine by season of treatment, treatment method, and insecticide

| Treatment variable | Tree mortality |
|---|---|
| | *Percent* |
| Season and duration of treatment (1,800 trees) | |
| Spring (18 months) | 2.2 |
| Summer (28 months) | 4.4a |
| Fall (22 months) | 3.8a |
| Treatment method (1,080 trees) | |
| Control | 2.0a |
| 1/3 bark streak (wound only) | 2.2a |
| 1/3 bark streak, 2% paraquat, insecticide | 3.1ab |
| 1/3 bark streak, 5% paraquat, insecticide | 4.0ab |
| 1/3 bark streak, 5% paraquat, no insecticide | 5.8b |
| Insecticide (720 trees) | |
| BHC | 2.8a |
| Dursban (chlorpyrifos) | 3.3a |
| Reldan (chlorpyrifos-methyl) | 4.6a |

Within a variable, means followed by the same letter are not significantly different at $P = 0.05$.

## Effect of wound type, paraquat concentration, and paraquat dosage

Because the objectives and the treatments imposed differ among the following studies, each study is presented separately.

In the first study, a 140-acre block of loblolly pine plantation ranging in site index from 90 to 95 was selected, Between September and January, five different treatments were imposed: control, 1/3-circumfer-ence bark streak and 5 percent paraquat, drill hole and 5 percent paraquat, one dowel, and two dowels (2.04 lb of paraquat/$ft^3$ of dowel). All trees treated with paraquat were sprayed with 0.1 percent BHC in water to a height of 6 ft (Outcalt and Stubbs 1979).

After 18 months, the 1/3-circumference bark streak with 5 percent paraquat caused the least mortality among the treatments tested (table 3). Mortality after this treatment was not significantly greater than on untreated control plots. The drill-hole treatment caused higher mortality than the bark-streak treatment. This result was rather unexpected, because others have reported that, given equal paraquat concentrations, larger wounds result in a greater incidence of beetle attack. Both one- and two-dowel treatments caused unacceptable tree mortality--31 and 90 percent, respectively.

In a second study, 5 percent paraquat was again applied to single, 1/3-circumference bark streaks on loblolly pine, also sprayed with 0.1 percent BHC in water. Insect-caused mortality in this study was negligible; as in the first study, this treatment did not significantly increase mortality. Several treated plots had less mortality than controls, and the mortality rate throughout the study, 2 percent, was less than is normally present in stands of this age and stocking (Stubbs and Outcalt 1982).

A factorial design was employed in a third study (Stubbs and Outcalt 1982). Wound types were a 1/3-circumference bark streak or tree-injector incisions with a 1-1/4 in. blade and 4-in. spacing on centers. A paraquat concentration of 0.5, 2, 4, 6, and 8 percent was applied at a rate of 0.15, 0.40, or 0.65 ml/in. of wound. An untreated control was also included, giving a total of 31 different treatment combinations. Each of these was applied to two five-tree plots in loblolly plantations, age 22, at three locations. After treatment, all tree boles were sprayed to a height of 6 ft with 0.5 percent lindane in water. Past tests by others had indicated that bark beetle attack increased with increasing paraquat concentration. This study was particularly well suited to investigation of this relationship. Three months after treatment, beetle attacks were positively correlated with paraquat concentration for both the 1/3-circumference bark streak and the injector wounding methods (fig. 7). Although

Table 3.--Bark beetle attack and associated mortality of loblolly pine after four paraquat treatments

| Treatment[a] [b] | Beetle incidence before treatment | Beetle incidence at 18 months[c] | Mortality at 18 months |
|---|---|---|---|
| | - - - - - - - *Percent* - - - - - - - | | |
| Control | 4.1 | 4.1a | 0.4a |
| Bark streak, 5% paraquat | 4.2 | 6.0ab | 1.5a |
| Drill hole, 5% paraquat | 5.7 | 12.4b | 6.9b |
| One dowel[d] | 2.8 | 19.0c | 31.0c |
| Two dowels | 6.7 | -- | 90.0d |

Means followed by the same letter within columns, are not significantly different at *P = 0.05*.

[a] 3,000 trees per treatment, except two dowels which had 10,000 trees.
[b] All but control trees were sprayed with 0.1 percent BHC in water.
[c] Live trees under attack.
[d] 2.04 pounts of paraquat per cubic foot of dowel.

attacks appear to be higher with the bark streak than with the injector at 4 and 6 percent concentrations, the difference is not statistically significant. When data from both wound types are combined, the result is a smooth curve with attacks increasing at an exponential rate

where: $Y = 0.81\ (1.61^{X}),\ R^2 = 0.99$

$Y$ = Percent of trees attacked

$X$ = Percent paraquat

The tree mortality shown in figure 7 also has a positive relationship with concentration, but it rises at a much slower rate. For this combination of wound methods, species and location, after 3 months it appeared that paraquat concentrations even moderately greater than 4 percent substantially increased insect problems (Outcalt and Stubbs 1979).

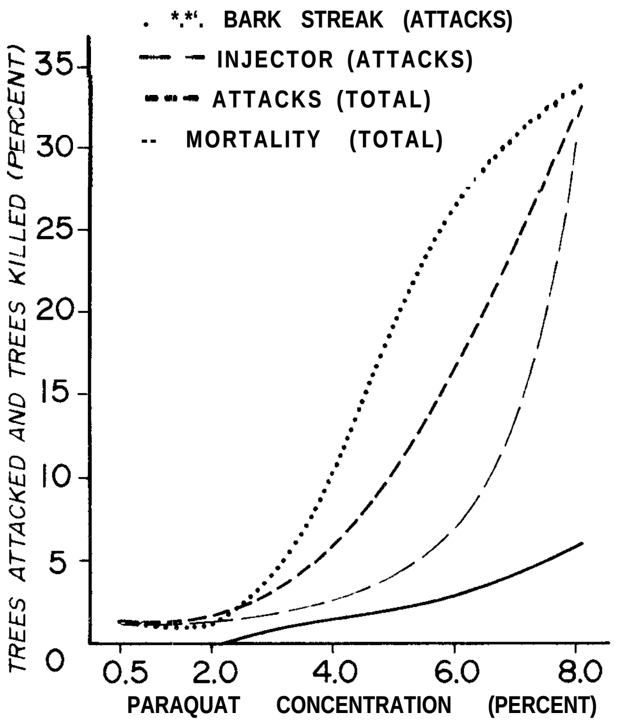


Figure 7.--Bark beetle attack and associated mortality of loblolly pine 3 months after treatment, as affected by application method and paraquat concentration.

However, after 12 months a somewhat different picture emerged (table 4). Tree mortality is of paramount importance, not rate of beetle attack, and mortality was negligible with paraquat concentrations less than 8 percent. The amount of paraquat solution that trees received had a very weak correlation with bark beetle attack and no correlation with tree mortality. On the average, the total amount of paraquat ion a tree received increased with increasing dosage. Thus it appears paraquat concentration, not quantity, is the key factor involved in bark beetle attack (Stubbs and Outcalt 1982).

Slash pine plantations were treated during May and June with 2 percent paraquat applied with a tree injector using a 1-in. blade and 5-in. spacing on centers. Following paraquat treatment, the tree boles were sprayed to a height of 5 ft with 1 percent BHC in diesel oil (Outcalt and Stubbs 1979). Tree mortality was low for the first 10 months after treatment (table 5). However, during the next 5 months, which corresponded to the second growing season, mortality increased to 13 percent. Because mortality decreased as tree size increased, stand volume loss was less--about 10 percent. Even though this loss is fairly high, about 2 cords/acre, our data indicate it will be more than offset by the value of the additional oleoresin. The break-even point of profit versus costs and losses is not reached until volume loss amounts to about 20 percent.

## Minimizing insecticide requirements in lightwood induction

Use of insecticide in preventive sprays immediately after paraquat treatment has become virtually standard practice. This insecticide application, however, accounts for 50 percent or more of the total cost of treating trees (Stubbs 1978), and it may be neither necessary nor effective, depending on the paraquat treatment used and evidently, geographic area. Results from earlier studies, wherein 2 or 5 percent paraquat was applied to bark streaks with very light or no application of insecticide, indicated that minimal tree mortality, 2 percent or less, was possible for at least 18 months thereafter (Moore 1978; Outcalt and Stubbs 1979).

Table 4.--Bark beetle attack and mortality of paraquat-treated loblolly pine year after treatment by concentration, dosage (ml/in. of wound), and wounding method

| Paraquat concentration and solution dosage | Tree injector | | Bark streak | |
|---|---|---|---|---|
| | Beetle attack[a] | Mortality | Beetle attack[a] | Mortality |
| | Percent | | | |
| 0.5 percent | | | | |
| 0.15 | 7 | 0 | 7 | 0 |
| 0.40 | 13 | 3 | 7 | 3 |
| 0.65 | 0 | 0 | 7 | 0 |
| Average | 7 | 1 | 7 | 1 |
| 2.0 percent | | | | |
| 0.15 | 0 | 0 | 3 | 0 |
| 0.40 | 3 | 0 | 7 | 0 |
| 0.65 | 20 | 3 | 13 | 3 |
| Average | 8 | 1 | 8 | 1 |
| 4.0 percent | | | | |
| 0.15 | 3 | 0 | 3 | 0 |
| 0.40 | 3 | 0 | 27 | 7 |
| 0.65 | 10 | 3 | 23 | 3 |
| Average | 5 | 1 | 18 | 3 |
| 6.0 percent | | | | |
| 0.15 | 0 | 0 | 27 | 3 |
| 0.40 | 7 | 0 | 10 | 0 |
| 0.65 | 10 | 7 | 30 | 3 |
| Average | 6 | 2 | 22 | 2 |
| 8.0 percent | | | | |
| 0.15 | 13 | 0 | 33 | 3 |
| 0.40 | 43 | 13 | 27 | 0 |
| 0.65 | 53 | 47 | 33 | 0 |
| Average | 36 | 20 | 31 | 1 |

[a] Each attack entry is based on 30 trees; its corresponding mortality entry is on the same 30 trees.

Table 5.--Bark beetle attack and associated mortality of 14,200 slash pines after injection with 2 percent paraquat [a]

| Treatment duration | Park beetle incidence[b] | Cumulative tree mortality |
|---|---|---|
| | - - - - - Percent - - - - - | |
| Pretreatment | 1.5 | -- |
| 5 months | 4.0 | 2.2 |
| 10 months | 3.1 | 3.7 |
| 15 months | 3.2 | 13.2 |
| 22 months | -- | 18.9 |

[a]After treatment, all trees were sprayed with 1 percent BHC in diesel fuel to a height of 5 feet.

[b]Live trees under attack at the end of each period.

That evidence and the discovery that mixing Ethrel with paraquat would increase oleoresin yield (Peters and others 1978) suggested that, in the geographic area around the Savannah River Plant, certain paraquat treatments applied with minimal or no insecticide resin soaking with minor losses from insects. To test this theory, a factorial experiment incorporating Ethrel and other variables was installed. Study objectives were to identify the combination of season, wounding, and chemical treatment that would minimize insecticide requirements while inducing adequate resinosis in loblolly pine (Moore and others 1979).

The following factors were involved:

- Three blocks or locations
- Three seasonal treatment times (March, June, and November) within each block
- Two concentrations of lindane (0 and. 0.25 percent)
- Three concentrations of paraquat (0, 2, and. 5 percent)
- Two concentrations of Ethrel (0 and 10 percent)
- Two methods of paraquat application (1/3-circumference bark streak and tree injector).

The design was a split split plot (in season and. insecticide), with a complete factorial of paraquat and Ethrel levels with wounding methods, resulting in 12 factorial treatment combinations. The control (untreated trees) may be considered as an addition to these. Each of the three locations had three plots of 520 trees; each plot was randomly assigned to one of the three seasonal treatment dates. Within each of these 520-tree seasonal plots, the 0.25 percent lindane treatment was randomly assigned to one of two split plots. The 12 factorial treatment combinations plus the control were applied to subplots of 20 trees within both of the split plots of a given seasonal replication.

Wounding was done about 12 in. above the ground, either with a tree injector on 5-in. centers around the tree, or with a modified chain-saw chipper as a l-in. high, 1/3-circumference bark streak. Paraquat was applied at 1 ml per incision with the injector;* with the bark streak, the solution was sprayed on by a calibrated applicator as follows: trees in 6- through 8-in. d.b.h. classes received 3 ml; 9- through II-in. trees received 6 ml; trees 11 in. and greater received 9 ml. After paraquat was applied, the basal 12 ft of trees in designated split plots were sprayed with a water emulsion of 0.25 percent lindane.

With no insecticide protection, use of 5 instead of 2 percent paraquat increased tree mortality when applied in spring, but not in summer or fall (table 6). When treatments were applied during

*Throughout this paper, tree injector dosages are given in milliliters (ml) because the metering devices on the injectors are normally scaled in these units. For those wishing to convert, 1 ml = 0.0338 fluid oz.

the spring or summer, use of the tree injector increased mortality over that of bark-streak treatments. Addition of Ethrel increased tree mortality only when used during the summer. Overall, fall. treatments had significantly lower tree mortality than either spring or summer treatments.

This study demonstrates that season of treatment, wounding method, concentration of paraquat, addition of Ethrel, and use of insecticide can all affect tree mortality following paraquat treatment. Because of interactions, there was no one best treatment but rather a number of treatments that performed satisfactorily on the basis of tree mortality,, Nearly all paraquat treatments applied in the fall had very low mortality even without insecticide protection (table 7). For treating during the summer, paraquat plus Ethrel applied with a tree injector is not recommended unless a protective spray is used (table 8). Even with insecticide spray, tree mortality can be relatively high if the tree injector treatment is used during the spring (table 9). As in other studies, the 5 percent paraquat solution applied to a 1/3-circumference bark streak had consistently low tree mortality for all seasons, even with no insecticide spray. Therefore, all our data indicate that this is a safe treatment method for all seasons in this region, and it does not require the added expense of an insecticide spray.

Table 6.--Mortality of 2,895 loblolly pines without insecticide protection 1 year after paraquat treatment, by treatment season

| Treatment variable | Tree mortality | | |
|---|---|---|---|
| | Spring | Summer | Fall |
| | - - - - - - *Percent* - - - - - - | | |
| **Paraquat concentration** | | | |
| 0 percent | 0.5a | 2.0a | 2.0a |
| 2 percent | 4.8d | 7.0b | 2.4a |
| 5 percent | 20.3c | 9.2b | 3.4a |
| **Wounding method** | | | |
| Chipper saw | 3.0a | 3.9a | 2.0a |
| Tree injector | 14.1c | 8.1b | 3.2a |
| **Ethrel concentration** | | | |
| 0 percent | 8.6b | 2.4a | 1.8a |
| 10 percent | 8.7b | 9.7b | 3.4a |
| **Average (890) trees, each group)** | 8.6a | 6.0a | 2.6b |
| **Control (75 trees, each group)** ' | 1.4 | 2.5 | 3.0 |

Within each treatment variable, means of a row or column followed by the same letter are not significantly different at

Table 7.--Mortality of loblolly pine 1 year after fall paraquat treatment

| Treatment | Tree mortality | | | |
|---|---|---|---|---|
| | Insecticide | | No insecticide | |
| | *Number of trees* | *Percent* | *Number of trees* | *Percent* |
| **5% paraquat** | | | | |
| Chipper, Ethrel | 0 | 0 | 1 | 1.6 |
| Chipper, no Ethrel | 0 | 0 | 0 | 0 |
| Injector, Ethrel | 0 | 0 | 5 | 7.0 |
| Injector, no Ethrel | 0 | 0 | 3 | 4.9 |
| **2% paraquat** | | | | |
| Chipper, Ethrel | 1 | 1.7 | 2 | 2.8 |
| Chipper, no Ethrel | 1 | 1.6 | 2 | 2.4 |
| Injector, Ethrel | 1 | 1.6 | 3 | 4.6 |
| Injector, no Ethrei | 2 | 3.0 | 0 | 0 |
| **0% paraquat** | | | | |
| Chipper, Ethrel | 1 | 1.8 | 2 | 2.5 |
| Chipper, no Ethrel | 0 | 0 | 2 | 2.8 |
| Injector, Ethrel | 1 | 1.5 | 1 | 1.6 |
| Injector, no Ethrel | 0 | 0 | 1 | 1.3 |
| **Average (890 trees, each group)** | 0.6 | 0.9[a] | 1.8 | 2.6[a] |
| **Control (75 trees, each group)** | 2 | 3.1 | 2 | 3.0 |

[a]Mortality of trees sprayed with insecticide was significantly less than that of unsprayed trees at *P = 0.05.*

Table 8.--Mortality of loblolly pine 1 year after a summer paraquat treatment

| Treatment | Tree mortality | | | |
|---|---|---|---|---|
| | Insecticide | | No insecticide | |
| | *Number of trees* | *Percent* | *Number of trees* | *Percent* |
| 5% paraquat | | | | |
| Chipper, Ethrel | 2 | 2.6 | 6 | 8.1 |
| Chipper, no Ethrel | 2 | 2.9 | 3 | 4.2 |
| Injector, Ethrel | 1 | 1.3 | 16 | 23.5 |
| Injector, no Ethrel | 0 | 0 | 2 | 2.5 |
| 2% paraquat | | | | |
| Chipper, Ethrel | 0 | 0 | 4 | 5.6 |
| Chipper, no Ethrel | 0 | 0 | 2 | 2.8 |
| Injector, Ethrel | 2 | 2.6 | 12 | 16.0 |
| Injector, no Ethrel | 0 | 0 | 2 | 2.9 |
| 0% paraquat | | | | |
| Chipper, Ethrel | 0 | 0 | 1 | 1.5 |
| Chipper, no Ethrel | 0 | 0 | 1 | 1.2 |
| Injector, Ethrel | 2 | 2.9 | 3 | 3.8 |
| Injector, no Ethrel | 0 | 0 | 1 | 1.3 |
| Average (890 trees, each group) | 0.8 | 1.0[a] | 4.4 | 6.0b[a] |
| Control (75 trees, each 'group) | 1 | 1.1 | 2 | 2.5 |

[a]Mean for sprayed trees significantly less than for unsprayed trees at *P = 0.05.*

Table 9.--Mortality of loblolly pine 1 year after a spring paraquat treatment

| Treatment | Tree mortality | | | |
|---|---|---|---|---|
| | Insecticide | | No insecticide | |
| | *Number of trees* | *Percent* | *Number of trees* | *Percent* |
| 5% paraquat | | | | |
| Chipper, Ethrel | 7 | 9.6 | 8 | 11.8 |
| Chipper, no Ethrel | 1 | 1.4 | 0 | 0 |
| Injector, Ethrel | 13 | 16.3 | 20 | 27.0 |
| Injector, no Ethrel | 5 | 7.4 | 31 | 41.9 |
| 2% paraquat | | | | |
| Chipper, Ethrel | 1 | 1.3 | 2 | 2.6 |
| Chipper, no Ethrel | 2 | 2.7 | 3 | 4.2 |
| Injector, Ethrel | 4 | 5.8 | 5 | 7.2 |
| Injector, no Ethrel | 3 | 4.2 | 4 | 5.3 |
| 0% paraquat | | | | |
| Chipper, Ethrel | 2 | 2.6 | 0 | 0 |
| Chipper, no Ethrel | 4 | 5.0 | 0 | 0 |
| Injector, Ethrel | 4 | 5.3 | 2 | 2.7 |
| Injector, no Ethrel | 1 | 1.4 | 0 | 0 |
| Average (890 trees, each group) | 3.9 | 5.3a[a] | 6.3 | 8.6[a] |
| Control (75 trees, each group) | 0 | 0 | 1 | 1.4 |

[a]Mean for sprayed trees is significantly less than that for unsprayed trees at $P = 0.05$.

It must be emphasized that these findings are not applicable throughout the South. The extent of the geographic region to which they apply is somewhat conjectural, but it is likely that they are reasonably pertinent from middle Georgia northward, provided that activity by the southern pine beetle is low. The need for different prescriptions, probably by regions, to control bark beetles after paraquat application is evident in the data presented by Drew (1978). For instance, lightwood treatments that can be applied with impunity in South Carolina may be disastrous in north Florida.

*Loss of Wood-Volume Growth*

Paraquat treatment causes tissue damage and necrosis, especially of the inner bark and cambium layer above the wound site. The bole area with dead tissue will produce no additional wood, and growth is probably reduced in areas with tissue damage. However, trees often produce compensatory growth as a response to wounding.

Thus, the question soon arose as to whether there was appreciable wood-growth loss due to paraquat treatment. Squillace and Moyer (1976) treated slash pine with 8 percent paraquat applied to a 1/3-circumference bark streak. After 20 months' treatment, they concluded that treated trees produced 29 percent less wood volume than the control trees during that interval. Drew (1980) computed growth loss on slash pine treated with 2 or 8 percent paraquat applied on a 1/3-circumference bark streak. The growth loss for a 2-year duration was 22 percent for the 8 percent paraquat treatment, but negligible for 2 percent paraquat. Testing the effects of 0.25 or 0.5 percent paraquat solutions placed in holes bored into the stumps of slash pines, Brown and Pienaar (1981) reported that the lower concentration produced no significant reduction in growth over a 2-year period, but the 0.5 percent concentration caused growth loss of about 13 percent.

Working with loblolly pine, Nix (1979) reported a 24 percent growth loss over a 2-year period from trees treated with 4 percent paraquat sprayed on a l/a-circumference bark streak. Two of the authors (Outcalt and Stubbs) attempted to determine growth loss in their several studies. They measured d.b.h. and height of thousands of trees before treatment and then prior to harvest, but this method was not sensitive enough to detect growth loss.

Most of these reported growth losses involve treatments more severe than we now recommend. For recommended treatments, we doubt that growth loss exceeds 10 or 15 percent for either slash or loblolly pines.

*Oleoresin Yields*

In this section we present only those oleoresin yields for paraquat treatments currently recommended, and which have been reported on a whole-tree basis, or can be computed to this basis. From these data we have often computed yields per cord, using these values: (1) 80 $ft^3$/cord of wood for both slash and loblolly pines; (2) an ovendry weight of 33 lb/$ft^3$ for slash pine, 31 lb for loblolly pine.

In slash pines (Joyce and others 1977), the increase in oleoresin yield attributable to paraquat treatment 2 years before appears to be from 100 to 125 lb/cord, 19 percent of which is turpentine and the rest resin acids. The data of Peters and others (1978) for slash pine give a per cord amount of about 90 lb of additional oleoresin after a 19-month treatment period. Data for a g-month treatment period (Roberts 1978b) give per cord oleoresin enhancement values of about 80 lb (20 percent turpentine) for slash pine, and about 43 lb (20 percent turpentine) for loblolly pine.

This gleaning is pitifully small, considering all the tests of paraquat induction of lightwood that have been made. This situation was one of the reasons the senior author, who was in a fortunate position to do so, determined to carry out large-scale tree sampling and oleoresin analyses. Results from studies by Stubbs and Outcalt (1982) are now presented.

In tests on loblolly pine, increases in oleoresin/$ft^3$ were determined on a whole-tree basis (bole to a 4 in. top). The 1/3-circumference bark streak and

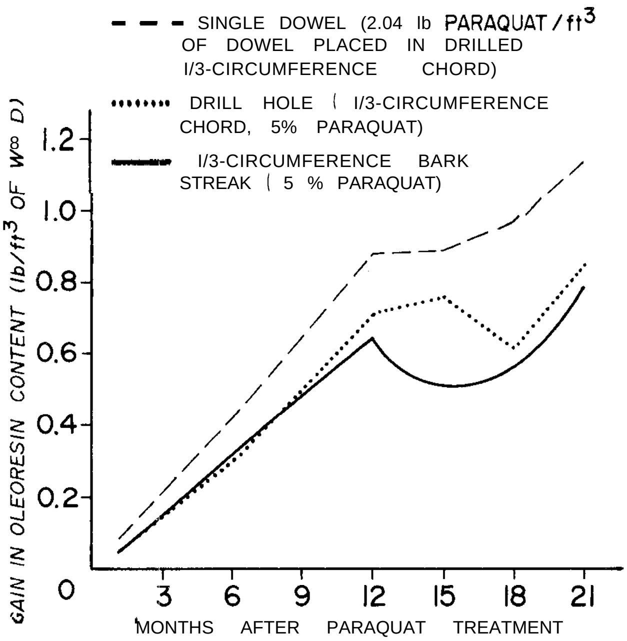


Figure 8.--Effects of three different methods of paraquat application on increases in oleoresin yield from loblolly pine.

the drill hole, with paraquat solution applied to the streak or into the hole, have given comparable increases in oleoresin content (fig. 8, table 10) but the drill-hole treatment had higher tree mortality from beetles (table 3). Higher yields were obtained by using a single paraquat-impregnated dowell in a drill hole, or by using two dowels, but tree mortality was prohibitive (table 3). In a variety of treatments using the bark streak and the tree injector on loblolly pine, the tree injector showed an overall superiority in oleoresin yield (table 11). Where degree of wounding, paraquat solution concentration, and season of treatment were equivalent, oleoresin content 12 months after treatment was about 25 percent greater for the tree-injector method. Taking insect problems into consideration with data from the same study, the tree injector used in the spring or fall with 2 percent paraquat plus 10 percent Ethrel, gave the best average yields (table 12) without undue losses to tree mortality (tables 7 and 9). This amounts to raising oleoresin content from about 65 lb/100 $ft^3$ to about 145 lb/100 $ft^3$.

Table 10.--Additional oleoresin content of loblolly pines at various times after paraquat treatment

| Treatment | Gain in oleoresin content after-- | | | | | |
|---|---|---|---|---|---|---|
| | 6 months | 9 months | 12 months | 15 months | 18 months | 21 months |
| | - - - - - - - - - - - lb/$ft^3$ - - - - - - - - - - - | | | | | |
| 1/3 bark streak, 5% paraquat | 0.31 ±.13 | 0.54 ±.09 | 0.64 ±.10 | 0.50 ±.10 | 0.57 ±.10 | 0.78 ±.11 |
| Drill hole, 5% paraquat | .29 ±.13 | -- | .69 ±.10 | .74 ±.10 | .61 ±.10 | .84 ±.11 |
| Drill hole, one dowel | .42 ±.13 | -- | .87 ±.10 | .88 ±.10 | .96 ±.10 | 1.13 ±.11 |
| Drill hole, two dowels | -- | 1.04 ±.18 | 1.09 ±.17 | 1.14 ±.17 | 1.13 ±.17 | 1.15 ±.19 |

Means are above; 95 percent confidence intervals are below.

Table Il.--Effect of treatment variables on total oleoresin content of loblolly pine 1 year after paraquat application, by season of treatment

| Treatment variable | Oleoresin content in-- | | | |
|---|---|---|---|---|
| | Spring | Summer | Fall | Mean |
| | - - -*Percent of dry* weight- - - | | | |
| Paraquat concentration | | | | |
| 2 percent | 4.23a | 3.43a | 3.91a | 3.86a |
| 5 percent | 4.48a | 3.8633 | 3.74a | 4.03a |
| Wounding **method** | | | | |
| Bark streak | 3.66a | 3.20a | 3.54a | 3.47a |
| Tree injector | 5.06b | 4.10b | 4.11b | 4.42b |
| Ethrel concentration | | | | |
| 0 percent | 4.23a | 3.49a | 3.71a | 3.81a |
| 10 percent | 4.48a | 3.81b | 3.94a | 4.08b |
| Control | 2.15 | 1.94 | 2.11 | 2.08 |

Values fcllowed by the same letter within columns are not significantly different at $P = 0.05$.

Table 12.--Additional oleoresin content of loblolly pine 1 year after various paraquat treatments, by season of treatment

| Treatment | Gain in oleoresin | | |
|---|---|---|---|
| | Spring | Summer | Fall |
| | - - - - - - - $lb/ft^3$ - - - - - - | | |
| 0% paraquat | | | |
| Bark streak, Ethrel | -0.02a | 0.09a | 0.04a |
| Injector, Ethrel | -.10a | .lla | .03a |
| 2% paraquat | | | |
| Bark streak | .39a | .38b | .40b |
| Bark streak, Ethrel | .50a | .29b | .42b |
| Injector | .82bc | .45bc | .59b |
| Injector, Ethrel | .89c | .73d | .84b |
| 5% paraquat | | | |
| Bark streak | .39a | .33b | .43b |
| Bark streak, Ethrel | .61ab | .55c | .53b |
| Injector | 1.01c | .75d | .58b |
| Injector, Ethrel | .91c | .75d | .49b |

Ethrel in all treatments was applied in a 10 percent solution of active ion by weight.

Within columns, values followed by the same letter are not significantly different at $P = 0.05$.

Slash pines injected with 2 percent paraquat in the summer doubled their oleoresin content after only 9 months (table 13). Oleoresin content continued to increase throughout the study, reaching over three times the normal level at 22 months. Unfortunately, tree mortality also increased throughout the study (see table 5), but this treatment was satisfactory over a 12-month period. Based on this study and others, treatments that have acceptable risk in tree mortality will raise oleoresin content from about 90 lb/100 $ft^3$ of wood to 190 lb or more. Athough the untreated slash pine oleoresin content as given in table 13 is about 65 lb/100 $ft^3$, 85 to 95 lb is more representative, especially for slash pine in the main slash pine belt.

In addition to yields on a whole-tree basis, it can be important to know how oleoresin is distributed in the merchantable bole. Tables 14 and 15 give oleoresin content of the first bolt, second bolt, etc. Because paraquat is applied at the base of the tree, and due to the nature of the resinosis process, the highest oleoresin concentrations are in the lower bole. For several years our industrial cooperators and others have examined the idea of combining an oleoresin extraction plant, using a hydrocarbon solvent process, with a pulpmill. Oleoresin-rich basal sections of a tree would be directed to the solvent extraction plant and the rest sent to the pulpmill. After extraction, chips from the solvent plant would also go to the pulpmill. In planning an operation like this, oleoresin yield data by tree section are obviously necessary. The advantages of solvent extraction are the production of higher quality oleoresin products than those from kraft pulpmill processes, and greater recovery of oleoresins.

Table 1.3.--Oleoresin content of slash pines at various times after paraquat treatment

| Treatment | Oleoresin content after-- | | | | | |
|---|---|---|---|---|---|---|
| | 6 months | 9 months | 12 months | 15 months | 18 months | 22 months |
| | lb/$ft^3$ | | | | | |
| Tree injector, 2% paraquat | 1.19 $\pm$.05 | 1.29 $\pm$.16 | 1.54 $\pm$.08 | 1.56 $\pm$.10 | 1.73 $\pm$.10 | 2.06 $\pm$.17 |
| Control | .65 $\pm$.07 | .65 $\pm$.07 | .65 $\pm$.07 | .65 $\pm$.07 | .65 $\pm$.07 | .65 $\pm$.07 |
| Gain | .54 $\pm$.12 | .64 $\pm$.17 | .89 $\pm$.13 | .91 $\pm$.17 | 1.08 $\pm$.16 | 1.41 $\pm$.19 |

Means are above; 95 percent confidence intervals are below.

## Oleoresin Quality

Oleoresin produced as a result of paraquat treatment is of comparable quality to that from untreated trees (Conley and others 1976; Enos and others 1978; Landry 1977; McBride 1977, 1978; Zinkel and McKibben 1978). Specific aspects of oleoresin composition are discussed next.

### Ratio of turpentine to resin acids

Analyses of oleoresin from paraquat-treated trees have virtually always shown a relative increase in the turpentine component as compared with control trees. In loblolly pine this amounts to a few percent gain, from 17 or 18 per-

Table 14.--Resin acids, turpentine, and oleoresin content of loblolly pine 21 months after paraquat treatment, by application method

| Bole section and component | Treatment | | | |
|---|---|---|---|---|
| | 1/3 bark streak | Drill hole | Dowel | Control |
| | - - - - - - - - - - - - - - lb/ft$^3$ - - - - - - - - - - - - - - | | | |
| 1st 5 ft | | | | |
| Resin acids | 2.19a | 1.96b | 1.97b | 0.62c |
| Turpentine | .73a | .59b | .57b | .12c |
| Oleoresin | 2.92a | 2.5613 | 2.5430 | .74c |
| 2nd 5 ft | | | | |
| Resin acids | 1.20a | 1.26a | 1.55b | .54c |
| Turpentine | .35a | .35a | .45b | .09c |
| Oleoresin | 1.55a | 1.61a | 2.00b | .63c |
| 10 ft to 4-in. top | | | | |
| Resin acids | .59a | .74b | 1.06c | .49d |
| Turpentine | .12a | .17b | .29c | .08d |
| Oleoresin | .71a | .91b | 1.35c | .57d |
| Whole tree | | | | |
| Resin acids | 1.10a | 1.16a | 1.38b | .54c |
| Turpentine | .31a | .31a | .39b | .09c |
| Oleoresin | 1.41a | 1.47a | 1.76b | .63c |

Means followed by the same letter within a row are not significantly different at $P = 0.05$.

Table 15.--Resin acids, turpentine, and total oleoresin content of slash pine 22 months after a tree-injector, 2 percent paraquat treatment

| Component | First 5 ft | Second 5 ft | 10 ft to 4 in. top | Whole tree |
|---|---|---|---|---|
| | - - - - - - - - - - - - lb/ft$^3$ - - - - - - - - - - - - | | | |
| Resin acids | 2.82<br>±.23 | 1.76<br>±.17 | 1.01<br>±.11 | 1.55<br>±.13 |
| Turpentine | 1.02<br>±.12 | .61<br>±.08 | .30<br>±.05 | .51<br>±.06 |
| Oleoresin | 3.84<br>±.33 | 2.37<br>±.23 | 1.31<br>±.14 | 2.06<br>±.17 |

Means are above; 95 percent confidence intervals are below.

cent of the total oleoresin to 19 to 21 percent (Stubbs and Outcalt 1982). The rest is, of course, resin acids. Slash pine normally has 20 to 21 percent turpentine and increases to about 25 percent after paraquat treatment.

**Turpentine composition**

Changes in turpentine composition differ in slash and loblolly pine following paraquat treatment. In slash pine there is an appreciable increase in the proportion of beta-pinene and some decrease in alpha-pinene compared with untreated trees (table 16). For loblolly pine there is a minor decrease in the proportion of beta-pinene after treatment but no change in the alpha-pinene percentage (table 17). Drew (1976) reported that beta-pinene from paraquat-treated slash pine in north Florida rose from 21 percent to 34 percent; a final report for the same study by Joyce and others (1977) gave values of 22 percent for controls, rising to 33 percent 24 months after treatment. Roberts (1978b) reported data for slash pine that show the beta-pinene component of turpentine increased from 22 to 28 percent. His data for loblolly pine show no significant decrease in the beta-pinene fraction but an increase in alpha-pinene from 61 to 64 percent. From the foregoing it is plain that except for beta-pinene in slash pine, paraquat treatment has little effect on turpentine composition.

Table 16.--Change in monoterpene composition of slash pine, by number of months after paraquat treatment

| Terpene | Injector | Control |
|---|---|---|
| | - - - *Percent* - - - | |
| **6 months** | | |
| Alpha-pinene | 62.8a | 67.0b |
| Beta-pinene | 24.6a | 19.1b |
| **12 months** | | |
| Alpha-pinene | 60.3a | 67.0b |
| Beta-pinene | 28.3a | 19.1b |
| **18 months** | | |
| Alpha-pinene | 59.3a | 67.0b |
| Beta-pinene | 28.4a | 19.1b |

Within rows, values followed by the same letter are not significantly different at *P = 0.05.*

**Resin acids composition**

From the discussion of Zinkel and McKibben (1978) and the data of Enos and others (19781, there appear to be no significant changes in resin acids as a result of paraquat treatment.

**Tall oil composition**

Paraquat treatment increases the resin acids content of the wood by 100 percent or more; therefore, the resin acids fraction of tall oil increases considerably. There has been no evidence that paraquat treatment increases fatty acids. In fact, there has been

Table 17.-.-Change in monoterpene composition of loblolly pine, by number of months after paraquat treatment

| Terpene | Bark streak | Drill hole | Dowel | Control |
|---|---|---|---|---|
| | - - - - - - - - - - - | - *Percent* - | - - - - - - - - - | |
| **12 months** | | | | |
| Alpha-pinene | 67.6a | 66.6a | 68.0a | 67.9a |
| Beta-pinene | 19.3ab | 19.6ab | 16.7a | 21 .Ib |
| **21 months** | | | | |
| Alpha-pinene | 67.3b | 63.9a | 62.9a | 64.9ab |
| Beta-pinene | 19.1a | 19.8ab | 18.4a | 21.9b |

Within rows, values followed by the same letter are not significantly different at *P = 0.05.*

concern that paraquat treatment reduces the yield of fatty acids, which at present are more valuable than resin acids. McBride (1977, 1978) reported that there appeared to be a decrease in fatty acids, as did Gill (1978). Conley and others (1976), 'however, found no significant change in fatty acids, nor did Enos and others (1978). Zinkel and McKibben (1978) give evidence for little or no change, and suggest that reported decreases were likely due to oxidation of samples, sampling problems, or both. We conclude that if there is a decrease in fatty acids, it is likely to be inconsequential.

**Paraquat residue**

Paraquat cannot be detected in the paper, turpentine, or tall oil produced by kraft pulp and paper mills (Earle 1975). Neither is paraquat to be found in the oleoresin products produced by wood naval stores extraction plants (Enos and others 1978).

***Economics***

Treatment Costs

The costs given in table 18 (Stubbs and Outcalt 1982) are presented on the basis of cubic feet of wood, because this sort of wood-volume measurement is least subject to variation. A cord may vary in actual solid wood content from 70 to nearly 100 $ft^3$. Data are also given on a per tree basis, because tree size enters into costs based on volume. It is emphasized that these costs are in no sense absolute, due to inflation, availability and cost of labor, and many other factors, but are nonetheless useful and valid for treatment comparisons.

The chipper or bark-streak method, in which horizontal 1/3-circumference wounds are made with a power tool and then sprayed with paraquat solution, would appear to be the least expensive method. However, the per tree data show that use of the tree-injector method could be somewhat less expensive; this

Table 18.--Costs per 100 cubic feet of wood and per tree for five paraquat treatment methods

| Treatment method | Treatment | | | | |
|---|---|---|---|---|---|
| | Paraquat | Paraquat application | Insecticide | Insecticide application | Total |
| | - - - - - - - - - - - - - | - - Dollars | - - - - - - - - - - - - | | |
| Chipper (5% paraquat) | 0.12 (0.018) | 1.32 (0.21) | 0.15 (0.02) | 1.38 (0.21) | **2.97** (0.46) |
| Drill hole (5% paraquat) | 0.12 (0.018) | 2.88 (0.41) | 0.16 (0.02) | 1.40 (0.21) | 4.56 (0.66) |
| Tree injector (2% paraquat) | 0.11 (0.011) | 1.62 (0.16) | 5.76[a] (0.56) | 1.88 (0.18) | 9.37 (0.91) |
| Single dowel | 1.45 (0.210) | 2.55 (0.37) | 0.16 (0.02) | 1.40 (0.21) | 5.56 (0.81) |
| Double dowel | 2.16 (0.340) | 4.59 (0.73) | 0.15 (0.02) | 1.31 (0.21) | 8.21 (1.30) |

Values per 100 cubic feet are above; those per tree are below.

[a] Includes cost of diesel oil carrier; water used in all other spray applications.

treatment a8 applied was quite costly, because we used diesel'oil for the insecticide carrier. If water were used as in the other treatments, and if trees were of comparable size to those treated with a chipper (injected slash pines were smaller than the loblolly pines in chipper experiments), then the cost of treating 100 $ft^3$ would be about $2.65 as compared with $2.97 for the chipper method. Labor, paid at a rate of $4.15 per hour, accounts for about 85 percent of these costs. The drill-hole method is considerably more expensive than either the tree-injector or chipper methods, and. it shows no advantage in oleoresin production. Aside from the high treatment costs, neither dowel method is viable because of high mortality from bark beetle attack.

In previous sections of this paper we have shown that both bark-streak wounding with 5 percent paraquat, and tree-injector application with 2 or 5 percent paraquat, can be used on loblolly pine in South Carolina with no insecticide application whatever, with nominal losses to beetle attack. costs for such treatments were about $1.40 instead of $3/100 $ft^3$ of wood.

## Cost-Benefit Comparisons

In these comparisons we set the value of oleoresin at $0.07/lb and the value of wood at $16/100 $ft^3$. With the data presented in tables 10, 12, and 13, other values that the reader may consider more suitable can be readily substituted. We used a total treatment cost of $3/100 $ft^3$ for both the bark-streak and injector methods, of which $1.60 is for insecticide spraying. Use of Ethrel added $0.06/100 $ft^3$. Paraquat-treatment expenses can be regarded as either costs or investments; we considered them as costs and did not deduct from profit any interest on investment. The reader can do so, using any interest figure that is appropriate to the situation. In determining the value of additional oleoresin in tables 19, 20, and 21, we deducted the value of oleoresin lost in trees that died. Finally, we assumed that all the additional oleoresin gained by paraquat treatment would be recovered by the extraction plant. Actual recovery efficiency can vary from 50 to 90 percent, and readers should apply whatever percentages are reasonable for their operations.

For loblolly pine, the 1/3-circumference bark-streak or chipper method took a little over 6 months to reach the break-even point (table 19). Maximum profit is shown for a treatment duration of 21 months, but the 12-month duration would give a comparable return if interest on investment capital were deducted. Since tree mortality was very low for this treatment, returns over time were primarily a function of increase in oleoresin content.

Regarding slash pine, if water had been used instead of diesel oil as the carrier for the insecticide spray, the paraquat treatment would have been profitable (table 20), assuming that this substitution would cause no appreciable increase in tree mortality. Tree mortality had more influence on profit in this slash pine study than that with loblolly pine, because mortality was higher and continued to increase throughout the test. But oleoresin also continued to accumulate at a fair rate, except for months 12 through 15. Thus, the maximum test time, 22 months, is financially the best harvest time even after deductions for mortality loss both in wood and oleoresin. The dip in expected profits at 15 and 18 months is caused by the previously mentioned temporary leveling in oleoresin accumulation, but a continuing tree mortality.

As shown by information presented in table 21, an insecticide spray on loblolly pine in the study region usually does not pay. Treatment costs can be halved by not spraying; an insecticide spray does not afford a sufficiently high level of protection, and some treatments simply do not require insecticide protection. The difference in tree mortality between sprayed and unsprayed treatments must be about 10 percent before spraying is worthwhile, if wood is valued at $16/100 $ft^3$.

Overall, summer treatments were poorest (table 21). In comparison with fall treatments, insect-caused tree mortality was greater but oleoresin yields were not, and spring treatments had much higher oleoresin yields. However, the

Table 19.--Cost-benefit analysis, per 100 cubic feet of wood, for 5 percent paraquat application to 1/3-circumference bark streak, on loblolly pine

| Treatment duration (months) | Value additional oleoresin[a] | Treatment cost | Value of wood lost[b] | Profit |
|---|---|---|---|---|
| | | *Dollars* | | |
| 6 | 2.17 | 3.00 | 0 | -0.83 |
| 9 | 3.78 | 3.00 | 0 | .78 |
| 12 | 4.48 | 3.00 | 0 | 1.48 |
| 15 | 3.50 | 3.00 | 0 | .50 |
| 18 | 3.99 | 3.00 | 0 | .99 |
| 21 | 5.38 | 3.00 | .22 | 2.16 |

[a]Based on an oleoresin value of $0.07 per pound.
[b]Losses due to tree mortality; wood valued at $16 per 100 cubic feet.

Table 20.--Cost-benefit analysis, per 100 cubic feet of wood, for 2 percent paraquat application to slash pine, by a tree injector

| Treatment duration (months) | Value of additional oleoresin[a] | Treatment cost | Value of wood lost[b] | Profit |
|---|---|---|---|---|
| | | *Dollars* | | |
| 6 | 3.77 | 3.00 | 0.13 | 0.64 |
| 9 | 4.40 | 3.00 | .42 | .98 |
| 12 | 5.83 | 3.00 | .91 | 1.92 |
| 15 | 5.72 | 3.00 | 1.54 | 1.18 |
| 18 | 6.65 | 3.00 | 1.89 | 1.76 |
| 22 | 8.53 | 3.00 | 2.21 | 3.32 |

[a]Based on an oleoresin value of $0.07 per pound.
[b]Losses due to mortality; wood valued at $16 per 100 cubic feet.

Table 21.--Profit or loss per 100 cubic feet of wood for several paraquat treatments of loblolly pine, by insecticide protection and season of treatment, 12 months after treatment

| Treatment | Insecticide | | | No insecticide | | |
|---|---|---|---|---|---|---|
| | Spring | Summer | Fall | Spring | Summer | Fall |
| | Dollars[a] | | | | | |
| 2% paraquat | | | | | | |
| Bark streak | -0.77 | -0.34 | -0.50 | 0.55 | 0.74 | 0.95 |
| Bark streak, Ethrel | .18 | -1.03 | -.44 | 1.53 | -.44 | .95 |
| Average | -.29 | -.68 | -.47 | 1.04 | .15 | .95 |
| Injector | 1.83 | .15 | .53 | 3.19 | 1.20 | 2.73 |
| Injector, Ethrel | 1.88 | 1.50 | 2.47 | 3.17 | .27 | 3.41 |
| Average | 1.85 | .82 | 1.50 | 3.18 | .73 | 3.07 |
| Average, 2% paraquat | .78 | .07 | .51 | 2.11 | .44 | 2.01 |
| 5% paraquat | | | | | | |
| Bark streak | -.53 | -1.22 | .01 | 1.33 | .14 | 1.61 |
| Bark streak, Ethrel | -.74 | .27 | .65 | .42 | .78 | 1.93 |
| Average | -.63 | -.47 | .33 | .87 | .46 | 1.77 |
| Injector | 2.37 | 2.04 | 1.06 | -3.99 | 3.30 | 1.68 |
| Injector, Ethrel | -.34 | 2.12 | .37 | -1.13 | -1.20 | .61 |
| Average | 1.01 | 2.08 | .71 | -2.56 | 1.05 | 1.14 |
| Average, 5% paraquat | .19 | .80 | .52 | -.84 | .75 | 1.46 |
| Average, 2 and 5 percent paraquat | .48 | .44 | .52 | .63 | .60 | 1.73 |

[a] Based on an oleoresin value of $0.07 per pound, wood valued at $16 per 100 cubic feet, and treatment costs at $3 per cubic foot with insecticide, $1.40 without insecticide.

best treatment for the summer season, 5 percent paraquat applied with a tree injector, did show one of the highest profits of any tested, regardless of season of application. Although tree mortality was highest after spring treatments, so was oleoresin yield. Therefore, profitability is attractive in spring treatments if paraquat concentration is limited to 2 percent. On the basis of yields, tree mortality, and profit potential, 2 percent paraquat with or without Ethrel applied with a tree injector during spring or fall had the best overall performance for loblolly pine. As noted previously, these data may not apply to the entire range of loblolly pine.

Ethrel increased oleoresin yield by an average of 15 percent (from data in table 12), which amounted to additional oleoresin of about 8 lb/100 $ft^3$ of wood treated. On this basis, the cost of Ethrel use was $0.06, the return $0.56 with oleoresin at $0.07/lb. However, averaging all treatments the use of Ethrel increased mortality from 1.8 to 3.4 percent, an average loss of $0.26/100 $ft^3$, so the average additional profit from the use of Ethrel was $0.56, -0.06, -0.26, or -0.24/100 $ft^3$ of wood treated.

Because of fluctuation in prices, the primary utility of tables 19, 20, and 21 is for comparing treatments and treatment durations, not profit projection. With the yield and mortality data presented in other sections of this report, it is possible to calculate profits based on whatever assumptions the reader believes are appropriate. A factor to consider in such calculations is growth, because changes in oleoresin yield on a per acre basis are dependent on oleoresin production, tree mortality, and tree growth. Profit on a $ft^3$ basis will always be less than profit on a per acre basis if there is any additional growth; i.e., at a given yield in lb of oleoresin/$ft^3$ of wood, added growth will produce more lb/acre of oleoresin.

### *Effect of Paraquat-Treated Pulpwood on Mill Operations*

#### Mill Trials With Loblolly Pine

Waite (197'7) reported a mill trial using wholly paraquat-treated trees, in volume about 480 cords. No difficulties were encountered, and the only operational differences noted were that the digesters gassed off harder due to the additional turpentine in the wood, and somewhat poorer pulp washing caused a saltcake loss of about 20 lb/ton of ovendry pulp. No loss in product quality occurred. Per ton of bleached pulp, an additional 0.8 gal of turpentine and 35.9 lb of tall oil were obtained. Two additional trials at the same mill involved 320 cords of treated wood as 40 percent of mill furnish, and 480 cords as 60 percent of furnish. Waite (1978) again reported that no significant problems arose and product quality was unaffected. Turpentine yields increased by 0.36 and 0.46 gal/ton of bleached pulp, with tall oil increases of 9.5 and 22.4 lb.

In a cooperative study with the U.S. Department of Energy and USDA Forest Service, Jonakin and Millard (1979) found that there were no detrimental effects to the pulpmill operations or to paper and chemical products. Approximately 4,500 cords of paraquat-treated wood were processed, supplying 25 percent of the mill furnish for 25 days. The treated wood produced about 40 percent more tall oil than did untreated wood, and the potential for increased turpentine production was at least as great, but the recovery system could not cope with the increased amount.

#### Mill Trials With Slash Pine

Landry (1977) gives details of a trial that used 4,000 cords of treated wood, making up 5, 15, and 25 percent of the mill furnish for 4 days each. No operational difficulties were noted, but the short time period for each subtrial produced sampling and byproduct inventory problems, making it difficult to determine the additional turpentine and tall oil gained. Similar difficulties plagued a second cooperative mill trial involving the U.S. Department of Energy, USDA Forest Service, and Continental Forest Industries (Stubbs and Outcalt 1982). About 1,100 cords of paraquat-treated slash pine supplied 12 percent of the pulpmill furnish over a 9-day period. No detrimental effects were observed during any phase of wood handling or pulping operations, and no lowering of product quality was detected. However, no significant increase in turpentine or tall oil could be determined due to problems similar to those of Landry (1977). The calibration period proved too short, and the differences were too small with only 12 percent of the total wood used having oleoresin enrichment.

#### Mill Trial Results

All of the mill trials must be considered successful. They demonstrate that paraquat-treated wood can be processed in quantity without disrupting papermill operations or reducing quality of products. Furthermore, the trials show that improvements will be needed in some mills in order to take full advantage of the increased oleoresin content of paraquat-treated wood.

## ENVIRONMENTAL IMPACT AND SAFETY

Paraquat has been used for agricultural purposes for more than 20 years. In his summary article, Calderhank (1968) discusses paraquat use as a herbicide and preharvest desiccant; its mode of action; fate in plants, soil, and water; and its toxicology. Because of the molecular structure and ionic charge of paraquat, it adheres strongly to organic materials and soil colloids. Paraquat applied to wood cannot simply be washed off. And soil colloids, which aside from organic matter are primarily clay minerals, hold paraquat so strongly that the only effective way of displacing it is to reflux with a strong acid. Normal soils have a tremendous capacity to absorb and inactivate paraquat. Even loamy sand, with 4 percent clay content, about as light a textured soil as can be found except in some sand dunes, is capable of absorbing about 56 lb of paraquat/acre in the surface 1 in. As an example of the quantity of paraquat entering an ecosystem with a typical paraquat treatment, use of 5 percent aqueous solution in stands with pulpwood-size trees amounts to distributing about 1.6 lb of paraquat/acre, and virtually all of that is taken up by the tree and remains there.

Because of this strong retention by soil colloids, ground water can contain no paraquat. If paraquat is placed in open water, it soon disappears due to uptake by weeds and algae, and eventual photochemical and biological degradation. Similar degradation occurs in terrestial ecosystems with the result that paraquat in soils and herbaceous plants is soon gone (Calderbank 1968). Paraquat in the wood of treated pines also degrades, but a residual is left at harvest time. Conley and others (1976) analyzed a freshly harvested pine for paraquat content 12 months after 8 percent paraquat had been applied to a 1/3-circumference bark streak, and found a paraquat residue of 4 parts per million. Paraquat in the wood of treated trees has a covering of bark, and even if it were on a bare wood surface it is not easily displaced. Thus, the hazard that paraquat-treated wood presents to either woods workers or wildlife is nil. There is no evidence that wildlife has ever suffered from the broadcast-type paraquat applications used in agriculture, and the manner in which it is used for lightwood stimulation must present even risk. Paraquat absorption in the gut is poor; the small amounts that might be ingested orally after a forestry operation would be rapidly and completely secreted. Paraquat properly used presents no threat to the environment (Calderbank 1968; Fletcher 1974).

After wood is taken to a pulpmill, the contained paraquat which is acidic meets the highly alkaline digester liquor and is promptly and totally destroyed; no paraquat can be found in the paper or byproducts (Earle 1975). The extraction processes used in the wood naval stores industry also result in oleoresin products free of paraquat (Enos and others 1978), because the paraquat residue remains in the wood chips.

There is no doubt that paraquat is poisonous and hazardous if not treated with due caution. Droplets can be absorbed through the skin or through the lungs, but known deaths have been caused primarily by oral ingestion. The oral lethal dose ($LD_{50}$) for humans is not well known, but seems to be about 30 mg/kg body weight (Fletcher 1974). For a man weighing 180 lb, this is equivalent to swallowing about 50 ml, 1.7 fluid oz, of 5 percent paraquat solution. The probability of accidentally swallowing this much is slight. Not only is paraquat ill-tasting, but it also burns the mouth. For a IO-year period, Fletcher (1974) reported three accidental deaths in the United States, a major user of paraquat. Treatment of paraquat poisoning has greatly improved, and with prompt medical attention, recovery is now 100 percent.

Benzene hexachloride (BHC) was the insecticide used in most of the studies discussed in this paper. It was only mildly hazardous as a pesticide, demanding only routine precautions. However, BHC has been banned from use and lindane, the gamma isomer of BHC, is now the standard insecticide for control of pine bark beetles.

## CONCLUSION AND RECOMMENDATIONS

Paraquat treatment for producing resin-soaked wood in loblolly and slash pines is on an operational basis, and has been for some time. The effects of recommended treatments can be predicted with more than adequate accuracy for loblolly pine. This information is based on scores of tests and experiments. The most useful paraquat experiments are of necessity both large scale and expensive, as typified by those of Stubbs and Outcalt (1982), made possible through the cooperation of the U.S. Department of Energy. These studies were conducted over a 4-year period, involved about 500 acres and 84,800 pines with volume totaling 1,221,000 $ft^3$, and required thousands of analyses for oleoresin content of cut sample trees. This sort of effort removed results of paraquat treatment, a highly variable phenomenon influenced by the many factors discussed in this paper, from what might be a random occurrence to virtual certainty. Using the recommended treatments for loblolly pine, oleoresin content will be more than doubled and tree mortality will be negligible, often not significantly different than in untreated stands.

Paraquat treatment effects for slash pine in the main slash pine belt may not be on as firm a basis, primarily because experimentation and subsequent sampling for oleoresin yield could not be made on as large a scale, and the balance of treatment intensity versus bark beetle hazard was more difficult to achieve. On the other hand, experimentation has continued for a much longer period in this region, and we have certainly learned what to avoid. The totality of research results, especially recent experiments, shows beyond reasonable doubt that if slash pine in this region is given the paraquat treatments we recommend in this section, oleoresin content will be doubled. Tree mortality will be acceptable--less than 10 percent after 1 year, usually 1 to 5 percent.

Whether paraquat treatment will be profitable for any one group depends on oleoresin enhancement, losses of oleoresin following tree harvest to the time the wood is processed, recovery efficiency of the mill or plant, the prices of oleoresin products, and the costs of treatment. Untreated slash pine containing about 90 lb oleoresin/100 $ft^3$ of wood will gain approximately 100 lb more oleoresin after recommended paraquat treatment; the gain in loblolly pine will be 65 lb or more/100 $ft^3$ from wood originally containing about 60 lb/100 $ft^3$. Losses of oleoresin after trees are cut and oleoresin recovery efficiency can both vary widely, depending on the procedures and processing of any one mill. Therefore, potential users of paraquat-induced lightwood technology will need to obtain estimates of these losses specific to their operation. Some capital investment in the mill, as in added settling tank capacity, may also be required. Unfortunately, oleoresin prices have historically been subject to much fluctuation. In this regard, pulp and paper companies with secondary processing, as in crude tall oil fractionation, are probably in the most favorable position. Because labor accounts for most of the treatment cost at present, mechanization could greatly reduce this cost. A satisfactory estimate of profitability can be made if reasonably accurate data on the above factors are obtained.

We believe that a major factor in slowing industrial use of lightwood technology is concern over possible bark beetle attacks on treated trees, subsequent mortality, and the creation of a large bark beetle population that will expand in all directions. The studies discussed here, which extended over a period of 10 years, show this apprehension to be unfounded. In the many lightwood induction studies we have conducted or been closely associated with, southern pine beetle populations were generally low but endemic populations of *Ips* spp. beetles were both active and opportunistic. *Ips* beetles are the ubiquitous enemy of paraquat-treated trees (Drew 1977, 1978). We had no difficulty in bringing about severe *Ips* beetle attacks and subsequent mortality if trees were given severe paraquat treatment. However, in no case did these heavily attacked stands become centers of spread to other stands. Adjoining stands showed no observable increase in either attack or mortality, and these included stands that had also been given paraquat but with a milder treatment,- We know of no instance in the South where heavily attacked, paraquat-treated stands have caused further beetle infestations. The reason seems to be that brood success, the development of larvae to adult beetles, is generally low in paraquat-treated trees.

We and others have found that beetle-attack hazard is directly correlated with the concentration of the paraquat solution used, rather than the absolute amount of cation applied. For slash pine, paraquat concentrations of more than 4 percent by cation weight are to be avoided, with 5 percent the limit for loblolly pine. If a tree injector is used with either pine species, paraquat concentration should not exceed 2 percent. Of secondary importance is the season when treatments are applied; in general the spring is worst, followed by summer. With loblolly pine, there is little insect problem after either fall or winter treatments. In the main slash pine belt, only winter treatments show less beetle attacks, but beetles are by no means inactive then. Avoid treating overstocked stands of poor vigor, especially slash pine, on mediocre or poor sites. Stands ripe for self-thinning, with or without the help of bark beetles, are poor investments for paraquat treatment even if beetle-caused losses are small.

In treating slash pine, for good oleoresin yields and acceptable losses from insects, we conclude that:

- Two percent paraquat concentration applied to a bark streak (chipper) wound, sprayed to the point of runoff, can be used throughout the year. The wound should be an in. in height and not exceed one-third of the tree's circumference. A protective spray of insecticide must be given to each tree at the time of paraquat treatment; use 1 percent lindane in a water emulsion sprayed to a height of 3 ft.

- Four percent paraquat can be applied to a 1/3-circumference bark streak in all seasons except spring. An insecticide spray as described in the preceding paragraph, is necessary.

- Tree-injector application must be used with caution, and not at all in the spring. Two percent paraquat concentration and no higher is recommended, with 0.4 to 0.5 ml per injector incision. If a 1-1/2-inch blade is used, incisions should be spaced on 5-in. centers. The same proportion of wounding should be maintained with other widths of blades by varying the distance between centers. An insecticide spray, as given earlier, is necessary. Tree-injector treatment will generally produce more oleoresin accumulation than will bark-streak wounding, but it also increases risks from bark beetle attacks.

- Treatment duration with slash pine is dependent on bark beetle activity. If activity is low, an 18-month period is recommended. As a rule, attack is prompt after treatment and its intensity can be assessed early. This is not always the case, however, and if mortality exceeds 4 or 5 percent in 8 months, the treatment duration should be limited to 12 months or less.

- We emphasize again that an insecticide spray is essential. If heavy bark beetle attack and subsequent tree mortality occur as the result of poor initial tree vigor, drought, or beetle epidemic, additional sprays are of little use and certainly not economic. The trees should be salvaged as soon as possible.

For treatment of loblolly pine north of middle Georgia, to produce the maximum oleoresin yield compatible with negligible losses from insects, our conclusions are:

- Five percent paraquat concentration applied to a 1/3-circumference bark streak can be used with impunity throughout the year. Insecticide sprays for this treatment are neither necessary nor useful. Adding a 10 percent Ethrel solution to this paraquat concentration will increase oleoresin yields, but do not add Ethrel to spring or summer treatments, or mortality may exceed 10 percent.

• Five percent paraquat should not be used in any season with the tree-injector wounding method.

• Use a 2 percent paraquat concentration with the tree injector. Space incisions as with slash pine. Injection usually results in a greater oleoresin yield than the bark-streak method, but injected trees are also more prone to insect-caused mortality. Spring treatment is marginal, but this method can be used the rest of the year without need of an insecticide spray. If 10 percent Ethrel is used with this treatment, summer applications should be avoided unless the trees are given an insecticide spray.

• Treatment duration for loblolly pine should be about 1 year. Yields will usually continue to increase beyond this period, but at a rate too low to be economically attractive.

• Insecticide sprays are not needed except in the preceding single instance with Ethrel. Treatments that demand insecticide spray protection may produce somewhat more oleoresin, but not enough to cover the spray costs.

• Loblolly pine south of middle Georgia should be given the same treatments with this important addition: An insecticide spray, as described under slash pine recommendations, is definitely required.

The best paraquat treatment for loblolly pine in terms of greatest profit potential, taking into consideration oleoresin yield, mortality loss, and treatment costs, is 2 percent paraquat, with or without 10 percent Ethrel, applied with a tree injector either in the spring or fall, without use of an insecticide spray if used north of middle Georgia. Data are insufficient to make as specific a recommendation for slash pine. The recommended treatments will increase oleoresin content by 100 to 150 percent, from about 65 lb/100 $ft^3$ to 125 lb or more in loblolly pine, and from about 90 lb/100 $ft^3$ to 190 lb or more in slash pine.

The operation of pulpmills demands much skill and high technology. To use them to determine changes in oleoresin yields is both cumbersome and complicated. Too many subtle things can happen to obscure oleoresin recovery results. This occurred in both of our cooperative pulpmill trials, particularly the one with slash pine, and it has occurred to some degree in every mill trial of paraquat-treated wood of which we are aware. However, the value of these trials is to demonstrate that there are few or no processing problems, to determine where improvements in the byproduct recovery system should be made, and to produce evidence that no decline in the quality of mill products occurs.

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A summary of research findings on the use of paraquat to produce resin soaking or bole xylem tissue in southern pines. Concentrations of paraquat, methods of application, expected yields, and likelihood of insect damage after treatment are discussed, and certain treatments are recommended.

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